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MOVING TARGET DETECTOR/AIRPORT SURVEILLANCE RADAR (ASR-7) FIELD--ETC(U)
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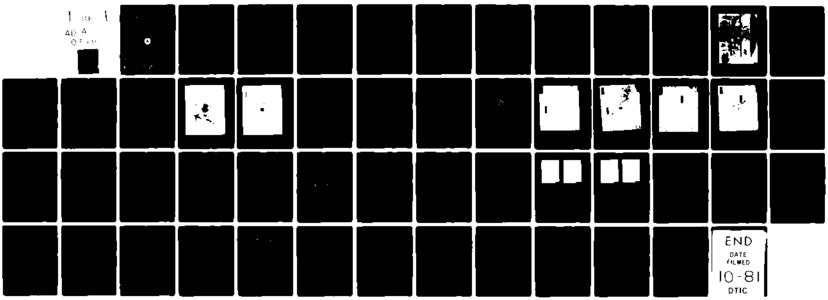

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MOVING TARGET DETECTOR/AIRPORT SURVEILLANCE RADAR (ASR-7) FIELD EVALUATION

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W. Goodchild

FEDERAL AVIATION ADMINISTRATION TECHNICAL CENTER
Atlantic City Airport, N.J. 08405

DEPARTMENT OF TRANSPORTATION
UNITED STATES OF AMERICA

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16. Abstract

The Moving Target Detector (MTD) II, a sophisticated radar processor, was evaluated to determine its capability to provide improved radar detection in an air traffic control (ATC) environment.

The MTD II was installed on one channel of an airport surveillance radar (ASR-7) at Burlington, Vermont. The major objective of testing was to compare the performance of the MTD II with that of the ASR-7 Moving Target Indicator (MTI).

This report concentrates on the comparative probability of detection, false alarm rate, MTI improvement factor, subclutter visibility, dynamic range, velocity response, and the simultaneous flight test results of the two systems. Comparison of the MTD II to the MTD I system is made when necessary to show major improvements or deficiencies in the MTD II design.

The results of the tests have shown that the MTD II provides surveillance capabilities superior to those of the ASR-7/MTI.

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Moving Target Detector Moving Target Indicator Radar Processor	Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

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Unclassified	Unclassified	50	

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METRIC CONVERSION FACTORS

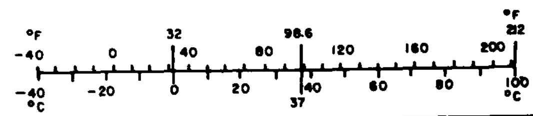
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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LIST OF ACRONYMS

A/D	Analog to Digital
ARTS	Automated Radar Terminal System
ASR	Airport Surveillance Radar
ATC	Air Traffic Control
CFAR	Constant False Alarm Rate
C&I	Correlation and Interpolation
CPI	Coherent Processing Interval
DSP	Digital Signal Processor
FFT	Fast Fourier Transform
FIR	Finite Impulse Response
I	Inphase
IEEE	Institute of Electrical and Electronics Engineers
MTD	Moving Target Detector
MTI	Moving Target Indicator
nmi	Nautical Mile
Pd	Probability of Detection
Pfa	Probability of False Alarm
PM	Processing Module
PMP	Parallel Microprogrammed Processor
PPI	Plan Position Indicator
Q	Quadrature
RAG	Range Azimuth Gating
RDAS	Radar Data Acquisition System
RDMS	Radar Data Measuring System
rms	Root Mean Square
SCV	Subclutter Visibility
SGP	Single Gate Processor
SP	Surveillance Processor
STC	Sensitivity Time Control
TTG	Test Target Generator

INTRODUCTION

PURPOSE.

The purpose of this project was to test and evaluate the Moving Target Detector (MTD) II performance in an operational environment at Burlington, Vermont. The MTD II surveillance capabilities were compared to the Airport Surveillance Radar (ASR-7) System.

BACKGROUND.

The MTD II is a sophisticated radar processor developed by Lincoln Laboratory under the guidance and sponsorship of the Systems Research and Development Service of the Federal Aviation Administration (FAA). Like the MTD I, the MTD II was designed to improve aircraft detection and lower the false alarm rate in all radar clutter environments.

At the conclusion of the testing and evaluation of the MTD I (reference 1), a decision was made to develop the MTD II for operational evaluation at selected field sites. The terminal version of the MTD II was subsequently compared operationally with the ASR-7 at Burlington, Vermont.

SYSTEM DESCRIPTION.

The MTD II equipment is shown in figure 1. Looking from left to right, the first equipment rack contains a Data General Eclipse S-130 minicomputer and recorder (used for processing primitive target reports), while the second rack houses the Megatek display system (all-digital display). The third rack contains the radar controller, the MTD II receiver, and the analog-to-digital (A/D) converters. The parallel micro-programmed processor (PMP) is in the fourth rack.

The MTD II was designed to improve radar detection of aircraft while simultaneously reducing false alarms from ground clutter, second-time-around ground clutter, precipitation clutter, "angel clutter," and interference. To provide the required clutter rejection, the MTD II uses wide dynamic range, coherent signal processing, velocity filtering, and adaptive thresholding.

A simplified block diagram of the MTD II system is shown in figure 2. The received intermediate frequency signal is processed in a linear receiver with a dynamic range of 54 decibels (dB). The receiver provides inphase (I) and quadrature (Q) video for two 10-bit A/D converters.

Data from the A/D converters for eight radar sweeps (coherent processing interval (CPI)) are stored in the PMP. The PMP provides the processing for the two-pulse canceller and seven-point finite impulse response (FIR) Doppler filters, thresholding, and weather detection. It outputs to the correlator and interpolator (C&I) the range, azimuth, amplitude, and Doppler information for each cell (1/16 nautical mile (nmi) by 0.6°) in which a threshold crossing was detected. The PMP independently processes 3,932,160 range-azimuth-Doppler cells.

The C&I processor correlates these thresholding crossings into targets and centroids them in range and azimuth. Following C&I, all the targets are subjected to independent geographical and Doppler adaptive thresholds to maintain the false alarm rate into the surveillance processor (SP) at 1×10^{-5} (approximately 40 false alarms per scan).

The target reports are then subjected to additional filtering in the SP. The SP is a scan-to-scan correlator used to reduce the false alarm rate to an average value of one false alarm per scan.

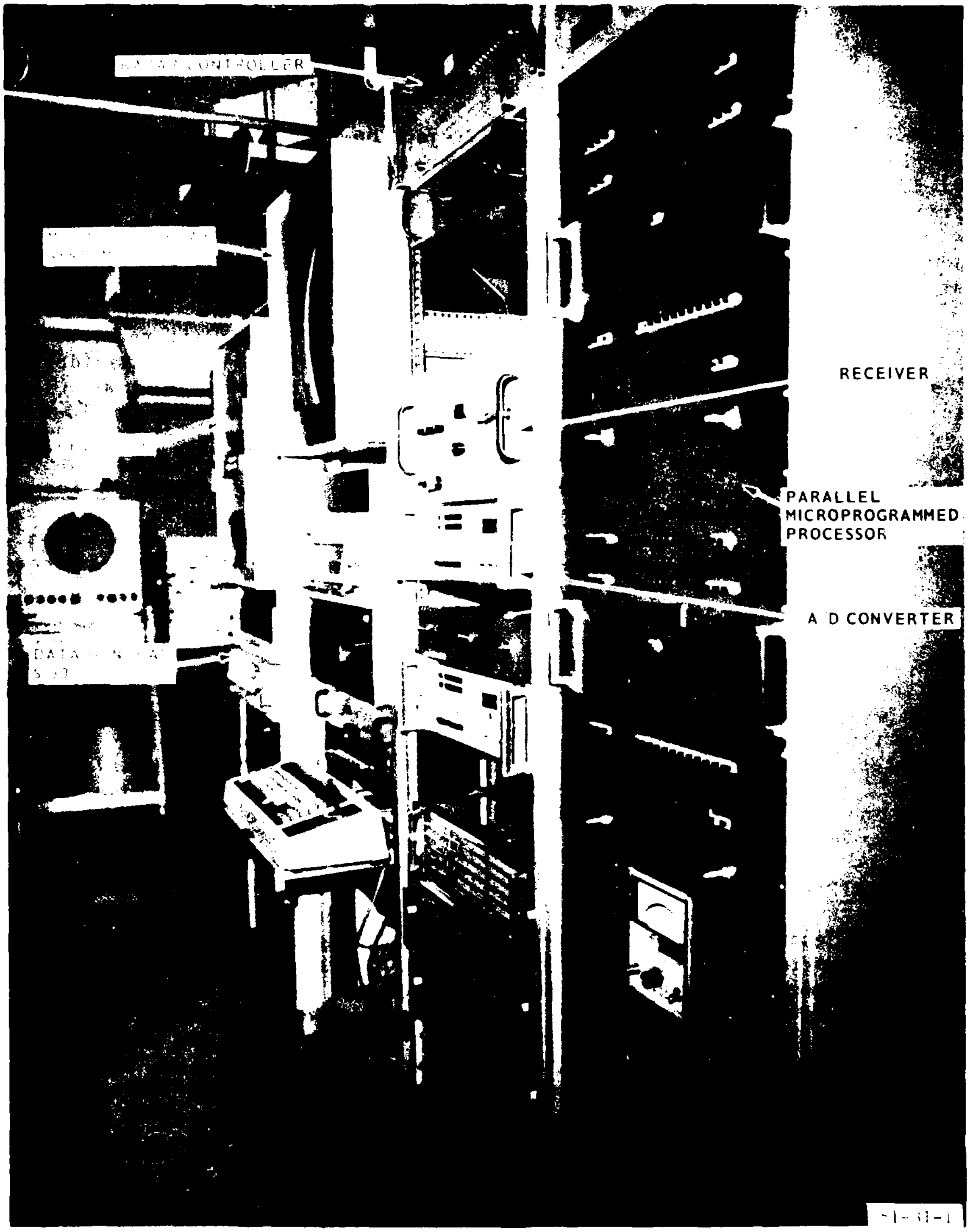

FIGURE 1.   MTD II EQUIPMENT

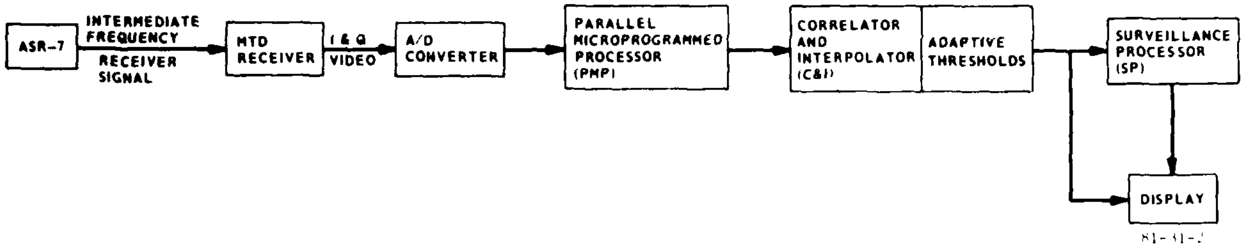

FIGURE 2. MTD II PROCESSOR, SIMPLIFIED BLOCK DIAGRAM

Both the outputs from the adaptive amplitude threshold and the SP are available to the air traffic controller.

A complete system description is provided in appendix A.

DISCUSSION

TEST CONFIGURATION.

The MTD II was evaluated in an operational environment as an integral part of the ASR-7 at Burlington, Vermont. Figure 3 is a block diagram of the MTD II/ASR-7 Test Bed.

To make the evaluation meaningful, the MTD II channel was operated simultaneously with the standard ASR-7 ATC channel. This was accomplished by diplexing the ASR-7 and realigning the triggers from the MTD II controller to prevent simultaneous transmission from both channels. Since the two channels were operated independently, interference resulted which was removed by adding a blanker to both channels. Channel B (standard air traffic control (ATC) channel) was blanked at video while the MTD II used a trigger from channel B to trigger the saturation detector. The only modification made on the ASR-7 MTD II channel (channel A) was to improve the stalo stability by replacing the standard ASR-7 stalo with a crystal-controlled, phase-locked oscillator. The three basic connections between the MTD II processor and the ASR-7 were triggers, coho signal, and the receiver preamplifier output. The system was configured in such a way that ATC, in the event of failure on channel B, could switch out the MTD II and channel A would operate in the standard ASR-7 configuration.

The PMP consists of a control unit and seven processing modules (PM's), each containing data memory and a processing element. Each PM independently processes 10 nmi of range while under microprogram control from the control unit. The seventh PM is used as a spare.

The PMP output (primitive target reports and weather) was sent on the Institute of Electrical and Electronics Engineers (IEEE) standard bus No. 488 to the post processor. The post processor, whose function is correlation and interpolation and scan-to-scan correlation of primitive targets, was implemented in a Data General S-130 computer. The output of the post processor (targets and weather data) was sent over the IEEE bus No. 488 to modems for remoting to the indicator site. The Megatek display (all-digital display) was used at the radar site to display MTD targets for maintenance and test purposes. The recorder was used to extract data in real-time and to provide data playback capabilities.

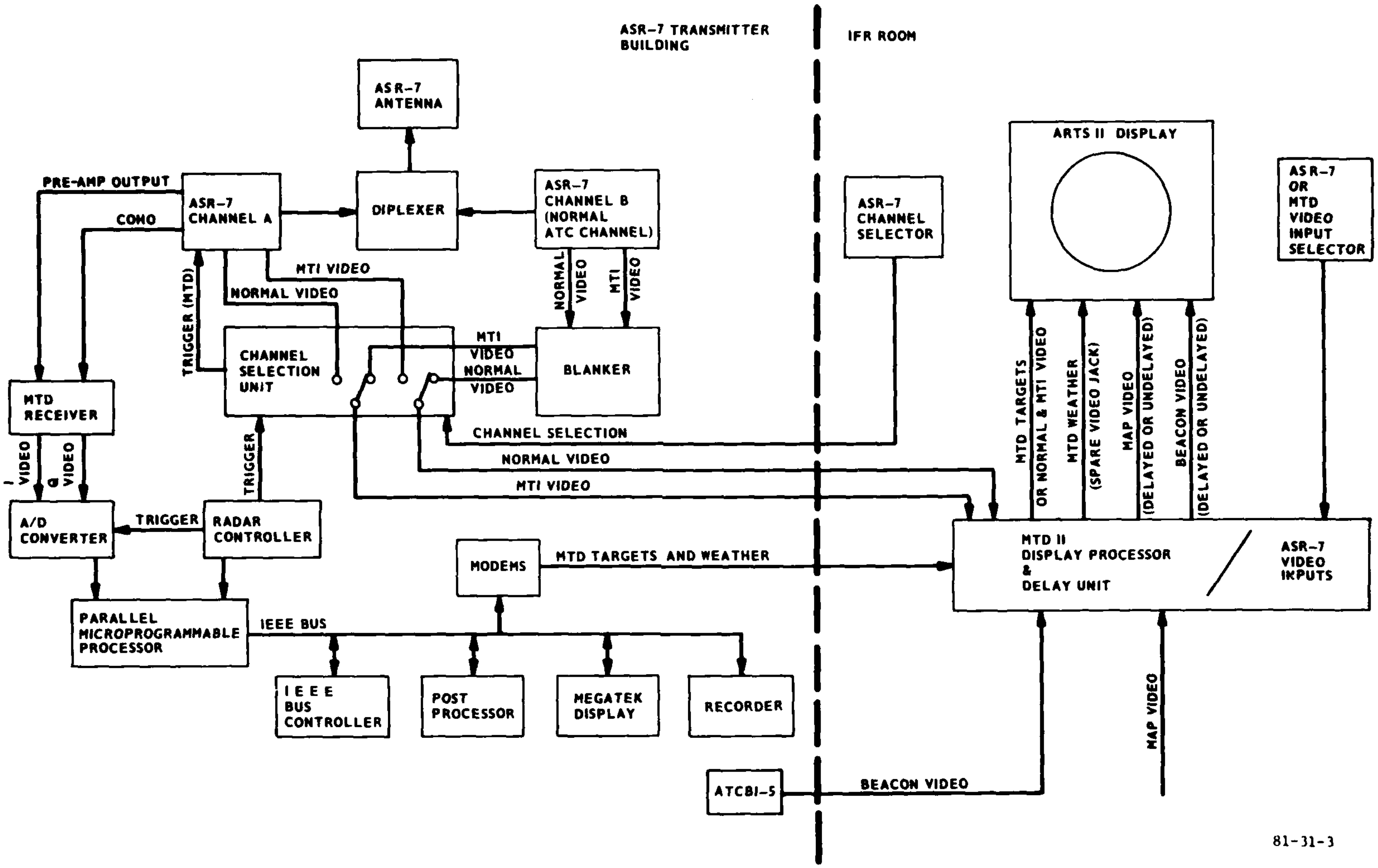

FIGURE 3. MTD II/ASR-7 TEST BED

The MTD II display processor permits simultaneous display of MTD target video, MTD weather contour video, beacon video, and map video on displays such as the Automated Radar Terminal System (ARTS) II or the FAA Series-7300 Plan Position Indicators (PPI's). The display processor delays beacon and map video (approximately one-third scan) to correspond to MTD processing delays. The display processor used in the field tests had the additional capability of switching between either standard ASR-7 inputs or those from the MTD.

SYSTEM TEST AND RESULTS.

PROBABILITY OF FALSE ALARM (Pfa). The MTD has an intricate network of thresholds whose purpose is to maintain the false alarm rate at the C&I output to 1×10^{-5} (40 false alarms per antenna scan) and at the SP output to no more than one or two false tracks per antenna scan in all radar environments. Only the fast acting threshold portion of adaptive amplitude censoring (see system description in appendix A) was functioning during the ATC evaluation. The full adaptive amplitude censoring (slow acting and fast acting thresholds) system was implemented too late to allow sufficient time for evaluation. Therefore, this report will not address the system false alarm rate, but only the false alarm rate in thermal noise, in ground clutter, and moving ground traffic. The system false alarm rate will be addressed in a subsequent report.

Pfa in Thermal Noise. In the MTD II there are 3,932,160 (960 range gates x 512 CPI's x 8 Doppler filters) opportunities for false alarm per scan. The thermal false alarm rate was measured as a function of root mean square (rms) noise level and threshold levels. The threshold was set in the digital signal processor (DSP) for filters 1 through 7 and for the zero filter at 13.8 dB and 15.56 dB, respectively, above rms noise, which resulted in a 1×10^{-5} Pfa. The difference in the threshold levels is due to the different constant false alarm rate (CFAR) losses for the two thresholding implementations.

The Pfa was determined by counting and averaging the number of false alarms as a function of system rms noise level for each Doppler filter over a 20-scan period and then calculating the Pfa.

$$\text{Pfa} = \frac{\text{Number of false alarms per scan}}{\text{Total number of opportunities per scan}}$$

Figure 4 shows the CFAR improvement of the MTD II over the MTD I. Since the Pfa of each Doppler filter was 1×10^{-5} per scan, it was not necessary in figure 4 to draw individual curves for each Doppler filter. A Pfa of 1×10^{-5} resulted in 40 false alarms per scan. The A/D converters used in the MTD I and MTD II had their least significant bits equal to 0.002 volt. The system was operated at 0.006 volt of rms noise (to mask truncation effects) in the MTD I and 0.0025 volt in the MTD II. This CFAR improvement of MTD II over the MTD I resulted in an increase of linear dynamic range of approximately 8 dB.

Pfa from Ground Clutter and Moving Ground Traffic. The MTD II field test site had extensive ground clutter. Figures 5 through 7 are PPI clutter strength photographs of the Burlington, Vermont, radar clutter environment. They show clutter extent and areas of clutter which exceed the stability performance of the system with and without Sensitivity Time Control (STC) clutter attenuation. Figure 7 shows all the ground clutter which exceeded the system linear dynamic range.

Potential false alarms from ground clutter and moving ground traffic obtained with the MTD II can be placed into four categories.

1. False alarms from ground clutter which exceed the stability of the system. (Stability is discussed later under MTI Improvement Factor Testing. The stability at Burlington, Vermont, was limited to 40 dB above rms noise.)

2. False alarms from ground clutter whose clutter spectrum width exceeds the design of the MTD II Doppler filters.

3. False alarms from ground clutter signals whose spectrum width has been increased by limiting.

4. False alarms caused by moving ground traffic.

To prevent false alarms from the first condition, a portion of the 0-velocity-filter threshold, which was directly proportional to the level of the ground clutter above the system stability level, was added to the mean level threshold of each Doppler filter.

To prevent false alarms from the second case, a portion of the zero Doppler filter, which was directly proportional to the level of the ground clutter above 35 dB, was added to the mean level threshold of Doppler filters 1, 2, and 6, 7. Since the 3 dB points of filters 1 and 2 or 6 and 7 were only 3.19 knots apart, the same amount was added to filters 1 and 2 or 6 and 7, and no velocity discrimination was obtained. This limited the MTD II subclutter visibility (SCV) in filters 1 and 2 or 6 and 7 to 27.5 dB. (See the section on SCV.)

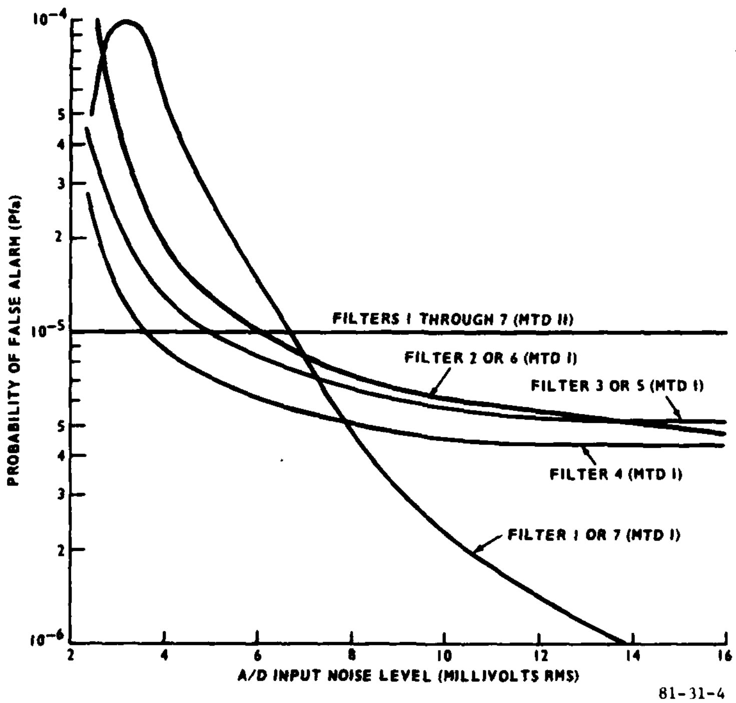

FIGURE 4. PROBABILITY OF FALSE ALARM FROM RECEIVER NOISE, FILTERS 1 THROUGH 7 (MTD I and MTD II)

FIGURE 5. BURLINGTON, VERMONT, GROUND CLUTTER, SENSITIVITY TIME CONTROL (STC) OFF

FIGURE 6. BURLINGTON, VERMONT, GROUND CLUTTER ABOVE 40 dB IN AMPLITUDE, SENSITIVITY TIME CONTROL (STC) OFF

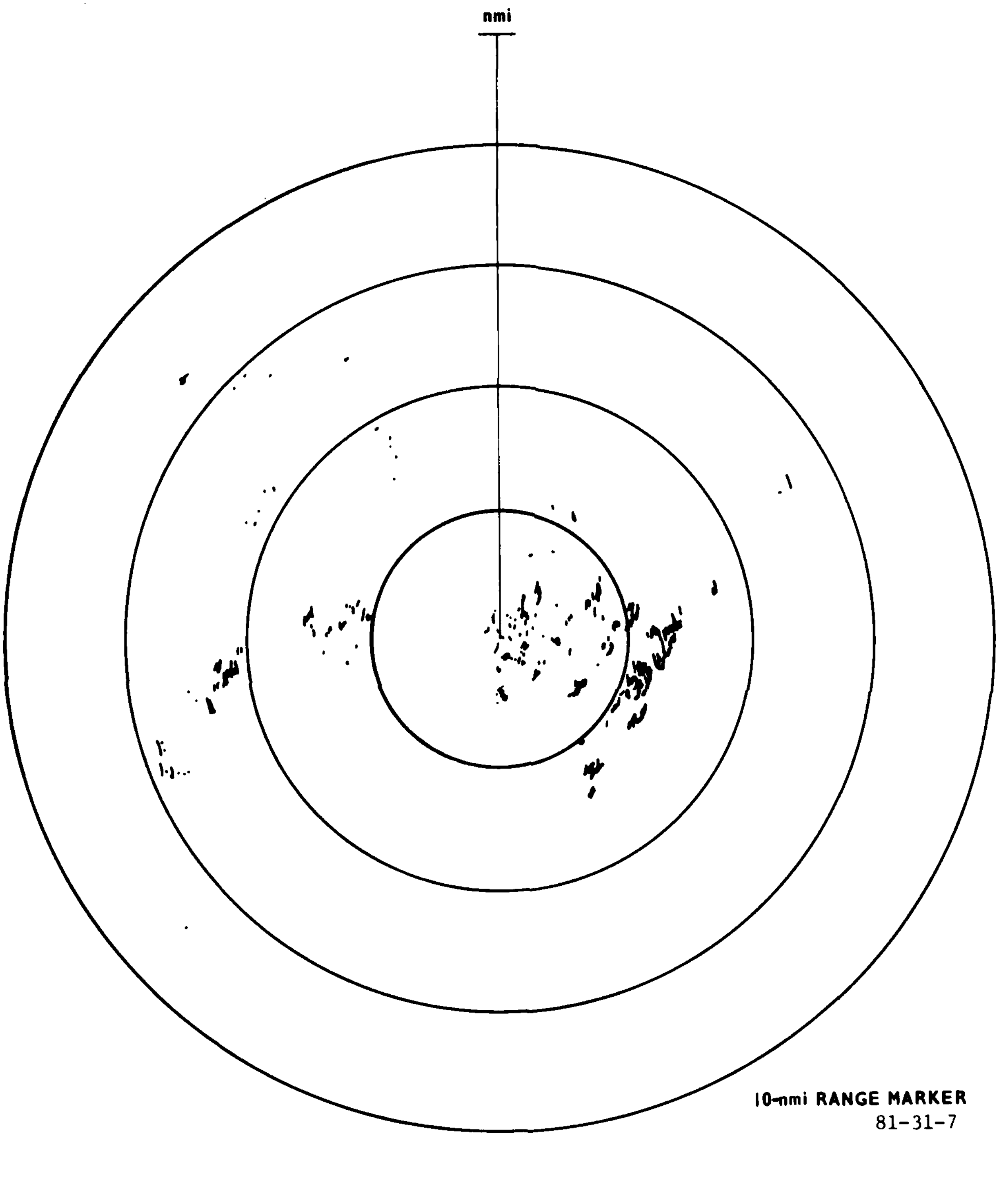

FIGURE 7. BURLINGTON, VERMONT, GROUND CLUTTER ABOVE 45 dB IN AMPLITUDE, SENSITIVITY TIME CONTROL (STC) ON

To prevent false alarms from cases 3 and 4, the contractor applied attenuation to the MTD II target signals as follows (there was no distinction made between ground clutter and moving ground traffic false alarms):

1. An R^{-4} STC curve was used to 13.75 nmi (figure 8). The radar echo power received from ground clutter, aircraft, and atmospheric anomalies (birds) varies inversely with the fourth power of range. The use of STC causes the radar receiver sensitivity to vary with time in such a way that radar echo strength is independent of range (reference 2).

2. Range Azimuth Gating (RAG) attenuation and censoring of selected range-azimuth-Doppler cells were used.

Figure 9 shows the geographical extent of these cells. Two types of RAG attenuation were applied (RAG 1 and RAG 2) as follows:

In all RAG 1 cells, 11 dB were added to the mean level threshold of all Doppler filters. No RAG 2 cells were processed. Each RAG cell was 3° wide by 0.25 nmi (four CPI's by four range gates) and contained a total of 128 range azimuth Doppler cells.

There were 388 RAG 1 cells and 217 RAG 2 cells for a total of 605. Therefore, 77,440 range-azimuth-Doppler cells were attenuated or censored.

To determine the benefit or degradation resulting from the attenuation and censoring, a computer program was written to count the number of false alarms which actually occurred in the RAG cells before applying the RAG censoring or attenuation. Data were extracted from more than 2,000 scans with the following results:

RAG 1 cell	105 false alarms average/scan
RAG 1 cell	115 false alarms maximum/scan
RAG 2 cells	13 false alarms average/scan
RAG 2 cells	17 false alarms maximum/scan

The above information was gathered on January 10, 1980, during daylight hours. The average total number of false alarms (118) which actually occurred per scan compared to the total number of range-azimuth-Doppler cells being censored or attenuated (77,440) represented a substantial attenuation of the MTD II. Figures 10 and 11 show the result of the RAG attenuation and the R^{-4} STC curve shown in figure 8. The affected areas are compared with the ASR-7/MTI system.

To overcome the target loss seen in figure 10, the ASR-7 antenna was tilted up from 2.0° to 4.7° during a scheduled radar service interruption to simulate the ground clutter reduction achieved by the use of a dual receive beam (passive horn) antenna. The RAG attenuation and censoring were removed from the system and the STC attenuation range was reduced to a maximum range extent of 7.7 nmi.

This resulted in a 1×10^{-5} false alarm rate from ground clutter and ground traffic while a high probability of aircraft detection was still maintained, as can be seen in figures 12 and 13.

Any ground clutter which exceeds the system limit level spreads the clutter spectrum, which increases the false alarm rate (clutter residue in

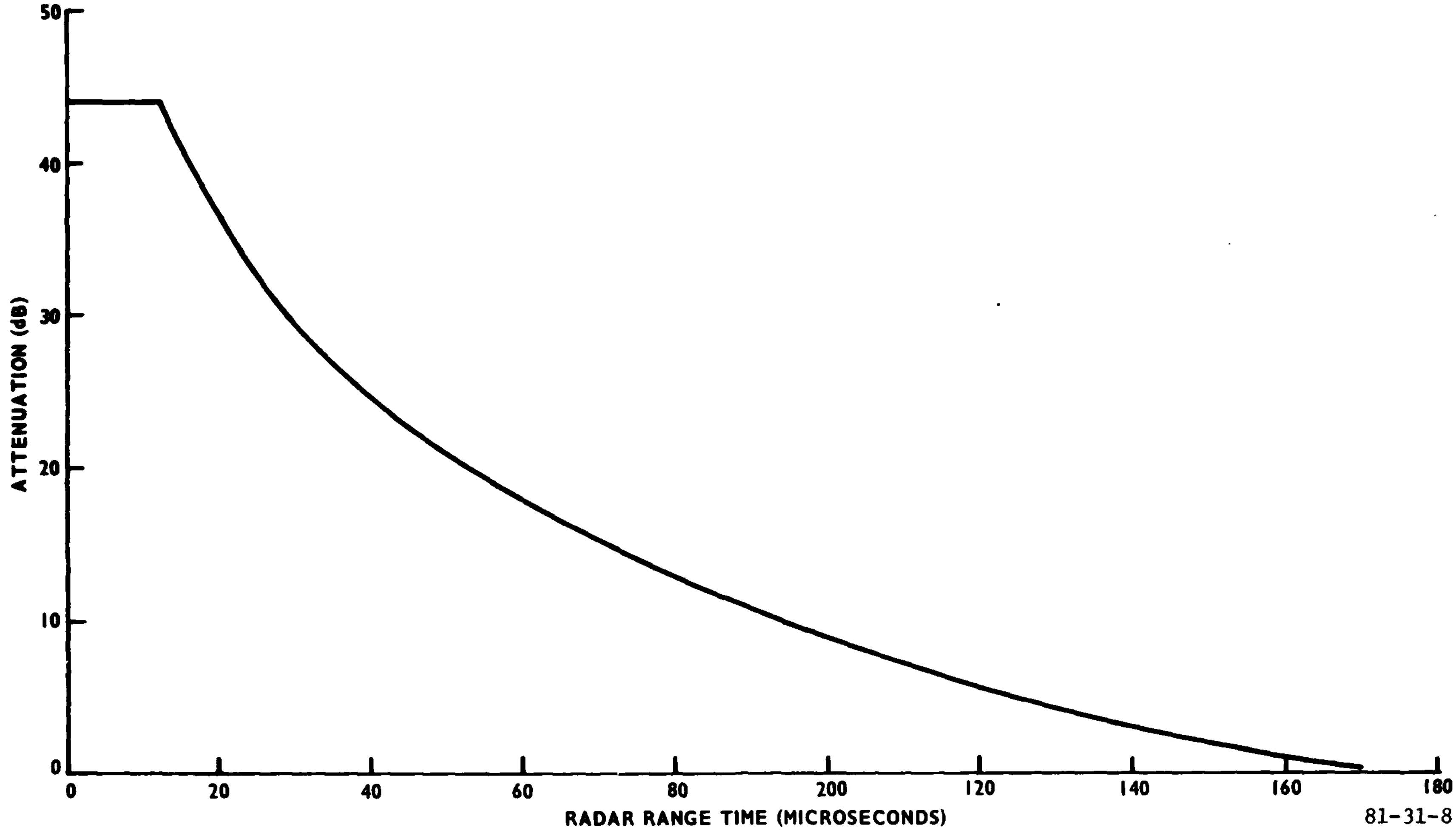

FIGURE 8. MTD II SENSITIVITY TIME CONTROL (STC) CURVE

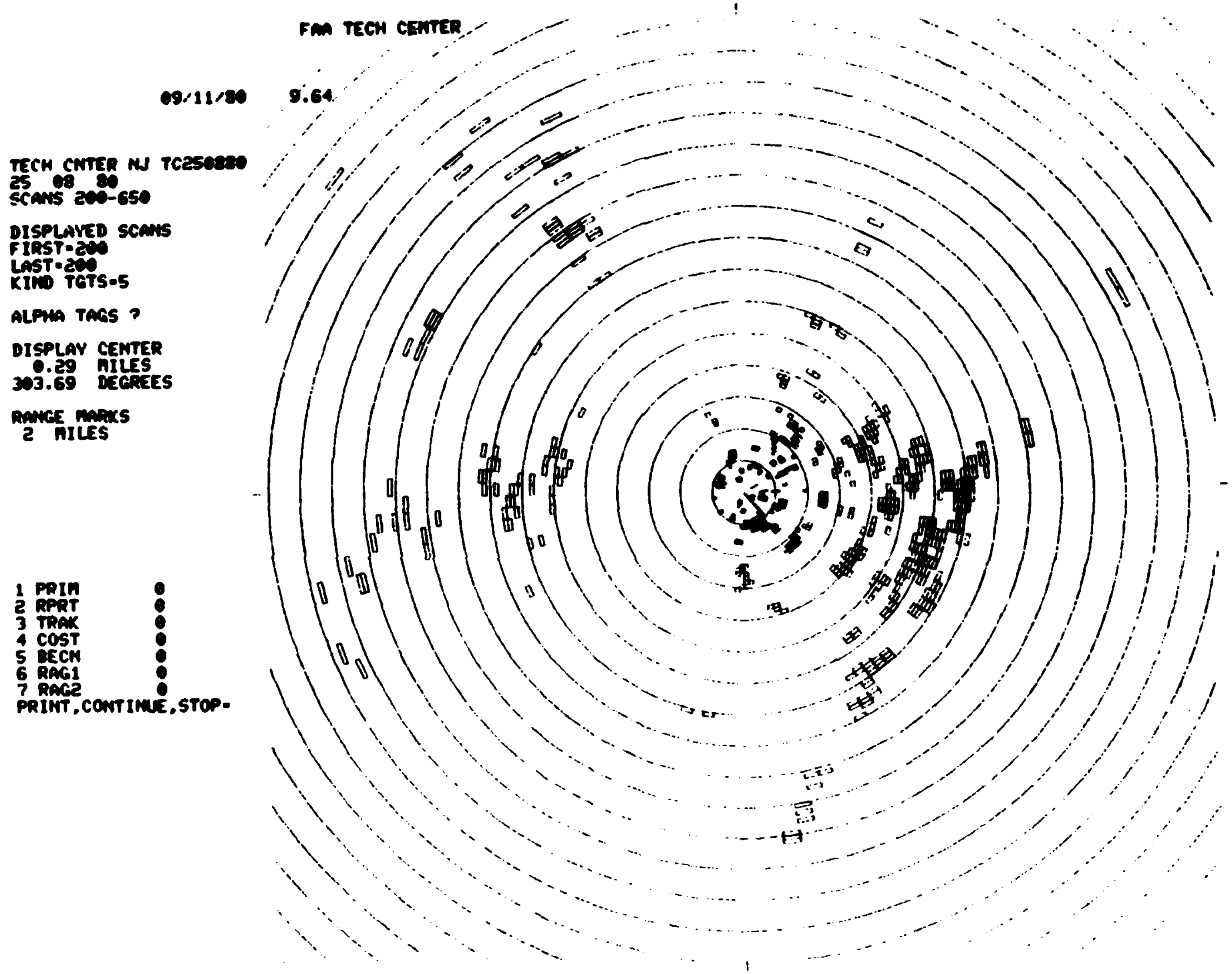

FIGURE 9. RAG ATTENUATION CELLS

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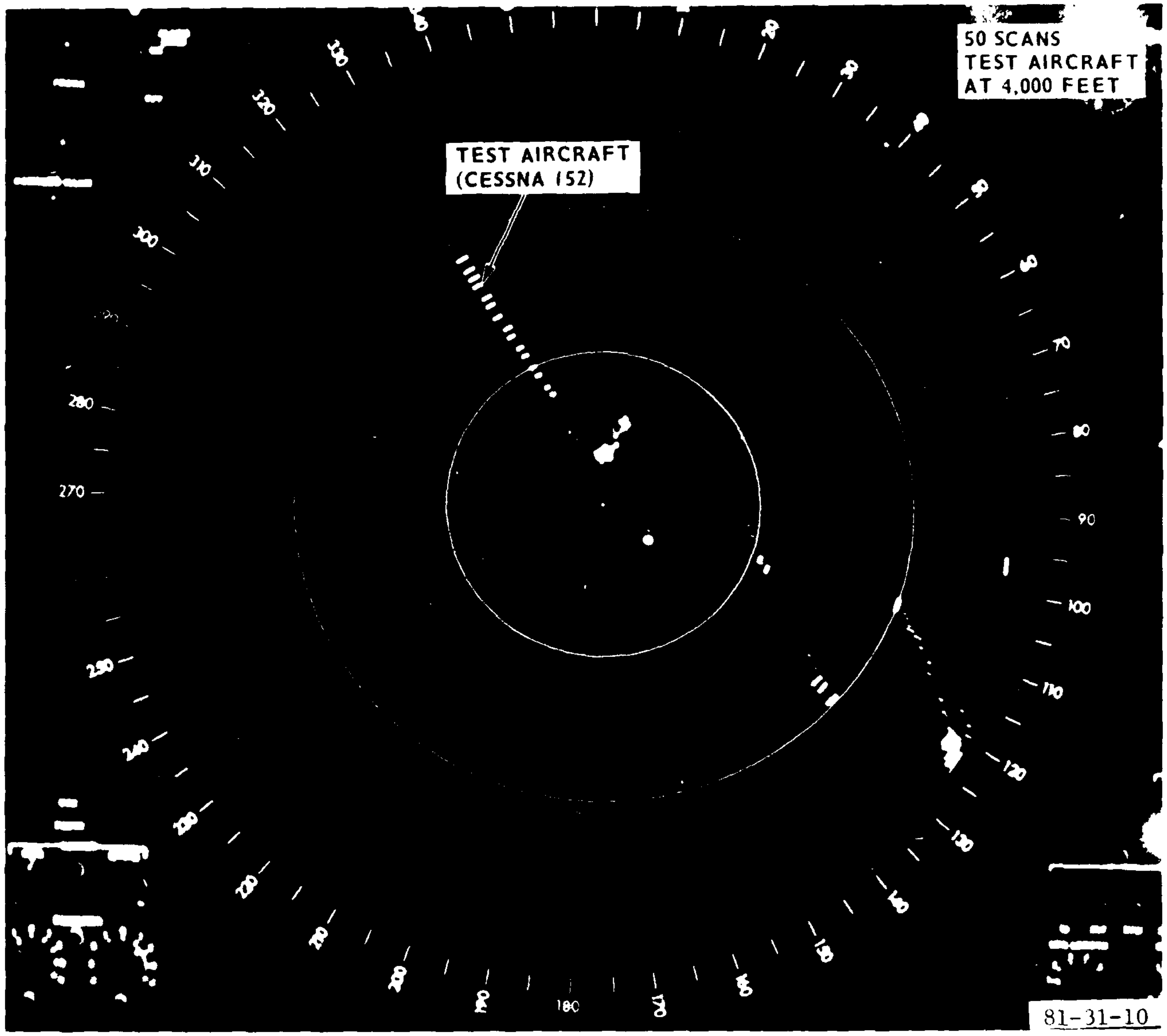

FIGURE 10. ASR-7/MTD II OUTPUT WITH THE ANTENNA TILT AT 2°

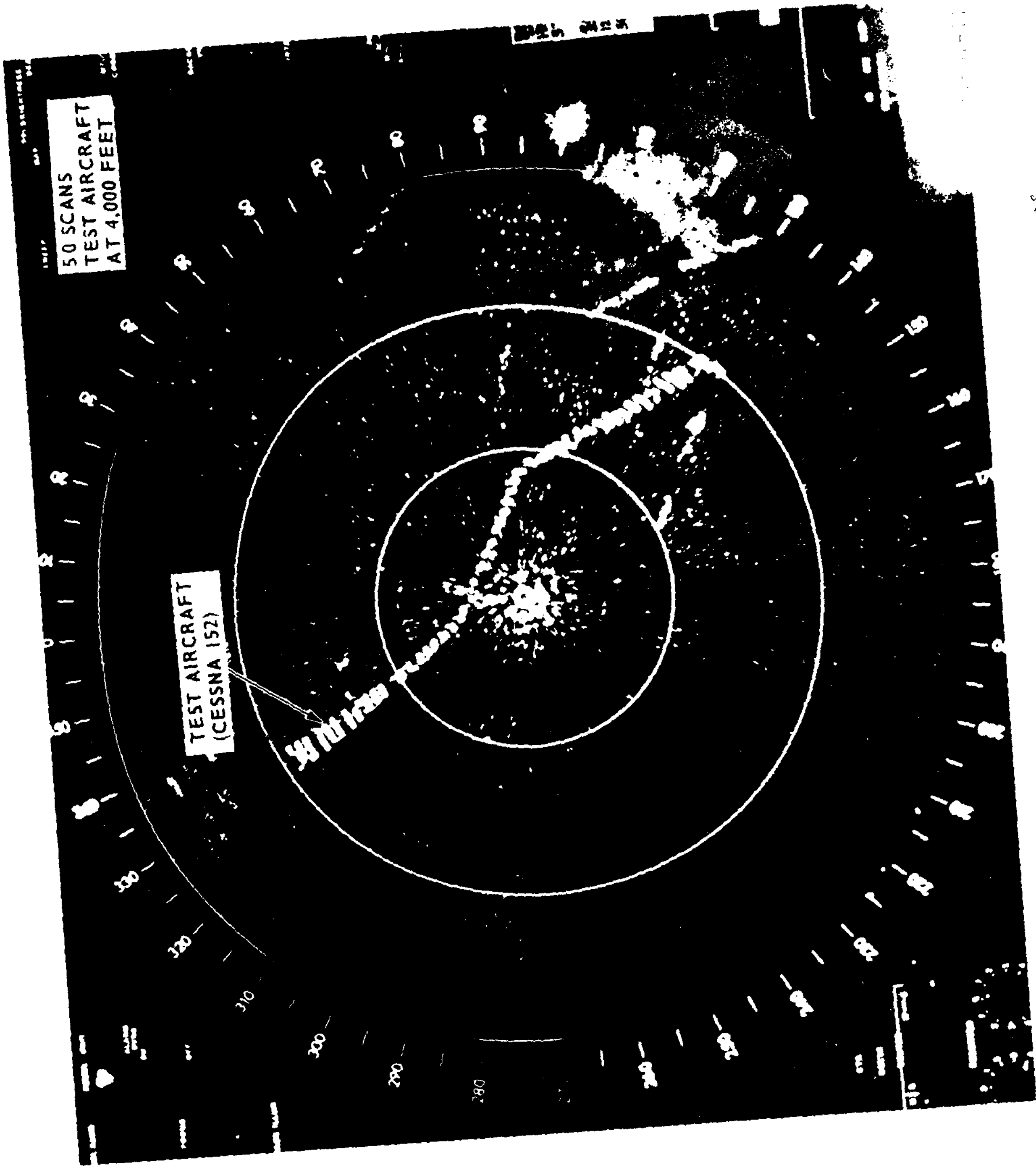

FIGURE 11. ASR-7/MTI OUTPUT WITH THE ANTENNA TILT AT 2°

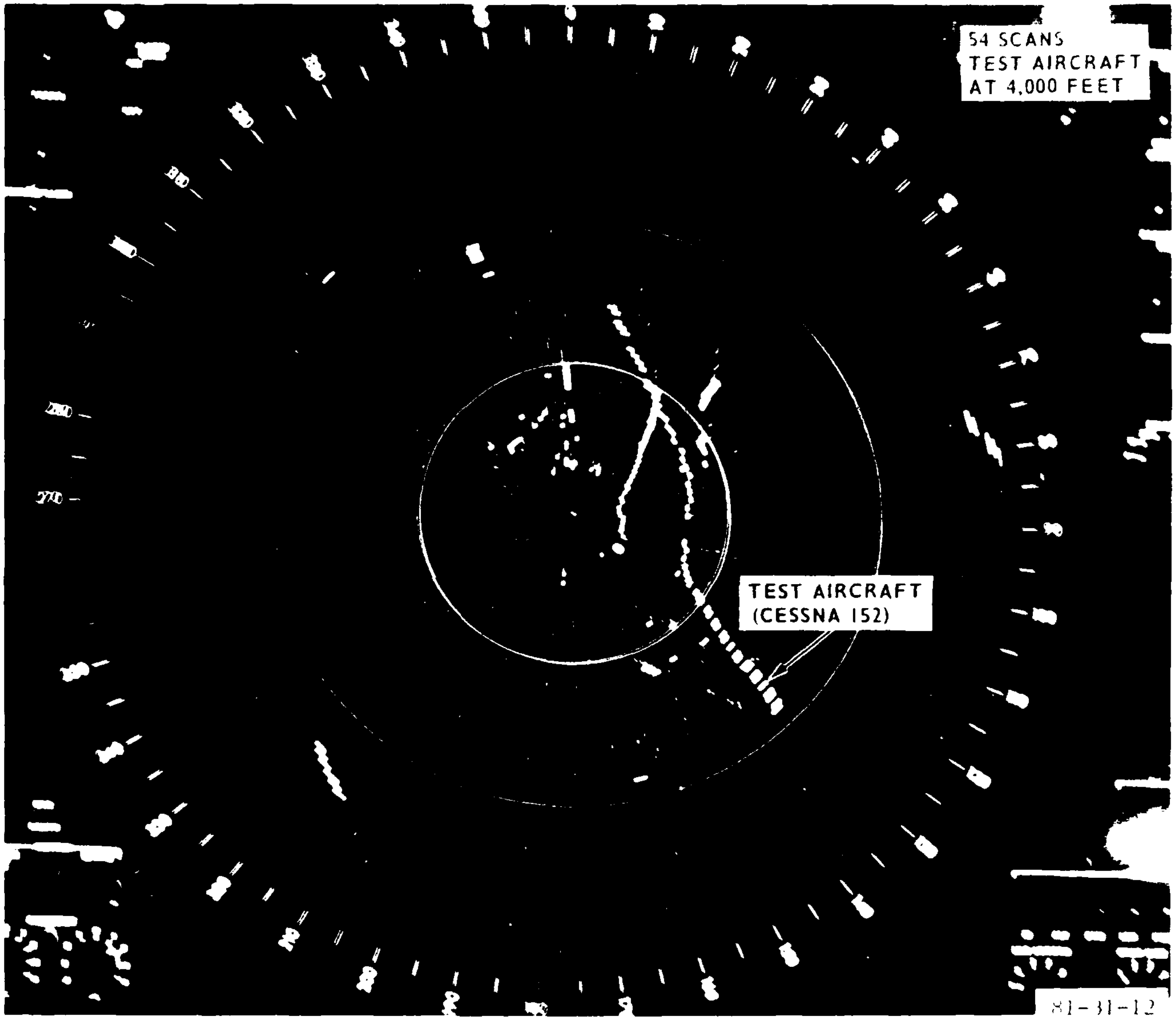

FIGURE 12. ASR-7/MTD II OUTPUT WITH THE ANTENNA TILT AT 4.7°

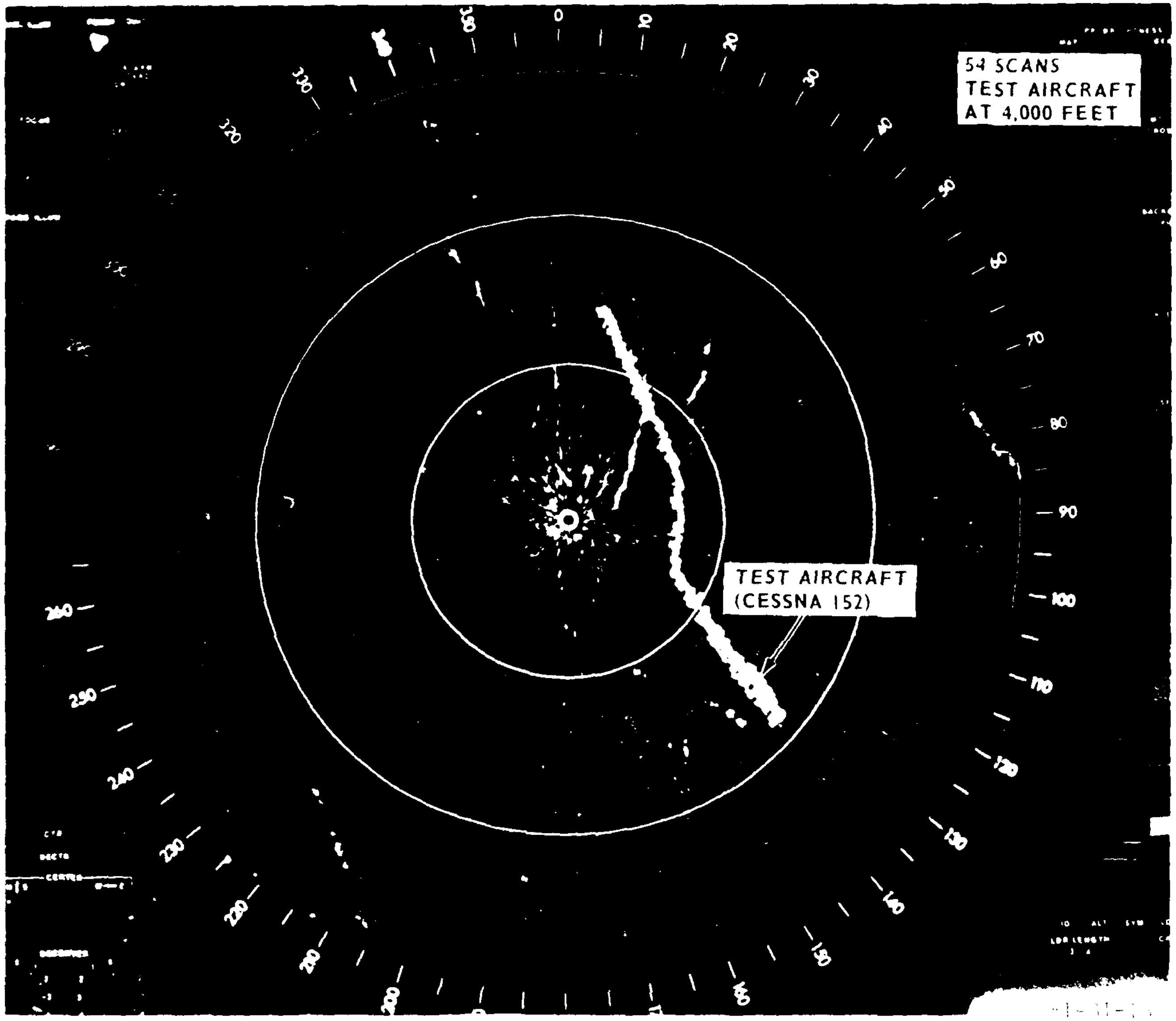

FIGURE 13. ASR-7/MTI OUTPUT WITH THE ANTENNA TILT AT 4.7°

conventional MTI systems) and reduces the SCV in both automated processors like the MTD II and the conventional MTI systems. In addition, ground clutter which exceeds the system stability level (see the section on ASR-7/MTD II improvement factor) will also generate false alarms. When an MTD or any automated system is operated in an extensive clutter environment, several things can be done to minimize the problems discussed above and still achieve good system operation. The suggested improvements are presented in appendix B.

The ground clutter and moving ground traffic false alarm rate from the ASR-7/MTI (clutter residue) as seen on the system displays is much higher than 1×10^{-5} (40 false alarms per scan). This required the mental threshold set by the air traffic controller to detect aircraft to be set to a level proportional to the false alarm rate. (This visibility factor will be discussed in detail later in this report in the section dealing with probability of detection.)

PROBABILITY OF DETECTION (Pd) IN THERMAL NOISE. The MTD II coherently processes eight pulses which provides a processing gain of 9 dB. However, the MTD II processing losses reduced the overall processing gain to 3.5 dB for Doppler filters 1 through 7. The processing losses for filters 1 through 7 were as follows:

0.5 dB	Azimuth weighting and straddling loss
2.0 dB	CFAR loss in MTD thresholding
1.3 dB	Average coherent gain loss of filters 1 through 7
1.0 dB	Range straddling loss
0.7 dB	Doppler filter straddling loss
5.5 dB	Total processing losses

The processing losses for the zero-filter were as follows:

0.50 dB	Azimuth weighting and straddling loss
3.86 dB	CFAR loss in MTD thresholding
5.00 dB	Coherent gain loss
1.00 dB	Range straddling loss
10.36 dB	Total processing losses

Azimuth weighting and straddling losses are incurred because the MTD CPI's are synchronized to the antenna position to update the clutter map each scan. The loss occurs when, for synchronization purposes, radar sweeps are not processed or a CPI is displaced from the center of the antenna beam by one or two sweeps. The CFAR loss is the result of the number of independent samples selected to determine the threshold level. The higher the number of samples used, the lower the CFAR loss. The average coherent gain loss is dependent upon the Doppler filter width. The range straddling loss occurs when the target echo is between two range gates. The Doppler filter straddling loss occurs when the target velocity is between two Doppler filters.

The theoretically possible 0.5 Pd of the MTD II (not counting processing losses using a nonfluctuating target) is obtained at a signal-to-noise ratio of 1.5 dB above unity (reference 3). Therefore, the calculated signal level for 0.5 Pd of the MTD II is 7 dB (1.5 dB theoretical plus 5.5 dB processing losses) for filters 1 through 7 and 11.86 dB for the zero-filter.

Unity signal-to-noise ratio at video was measured on the ASR-7 and MTD receivers in Burlington, Vermont, to be at -107 dBm.

The percent of detection of the MTD II was measured in thermal noise by using a coherent test target generator (TTG). The system Pfa was set to 10^{-5}. Thirty-two RF antenna (ASR-7 pattern) modulated test targets which moved in range according to the velocity being tested were inserted into the system. The TTG run length was set to match the two-way antenna pattern of the ASR-7.

Figure 14 shows the measured 50-percent detection of the MTD II at the surveillance processor input. Both the surveillance processor input and output were available to the air traffic controller. The surveillance processor requires three consecutive detections (three scans in a row) to initiate a track and will coast a track for three scans before dropping it. The surveillance processor output has a typical false track rate of one per scan. An increase of signal-to-noise ratio of 0.7 dB over the required 50-percent detection signal-to-noise ratio at the surveillance processor input will provide a 50-percent detection at the surveillance processor output. All MTD targets were displayed at maximum intensity level with a variation of run length to show strength.

The 50-percent detection of the ASR-7 system viewed on an analog display is, to a large degree, subjective. There are many factors which influence the optimum detection of a target on a radar PPI display. This discussion will not address all of these factors but will attempt to show only the difference in detection between an automatic thresholding device (MTD) and the operator who mentally sets the threshold level. The common reference used to compare the 50-percent detection of the MTD and the ASR-7 will be unity signal-to-noise ratio.

The smallest visible signal on a radar display occurs when the visibility threshold is reached by a target which can just be seen when the observer knows precisely where the target will occur (reference 4). This definition assumes that the display is optically adjusted

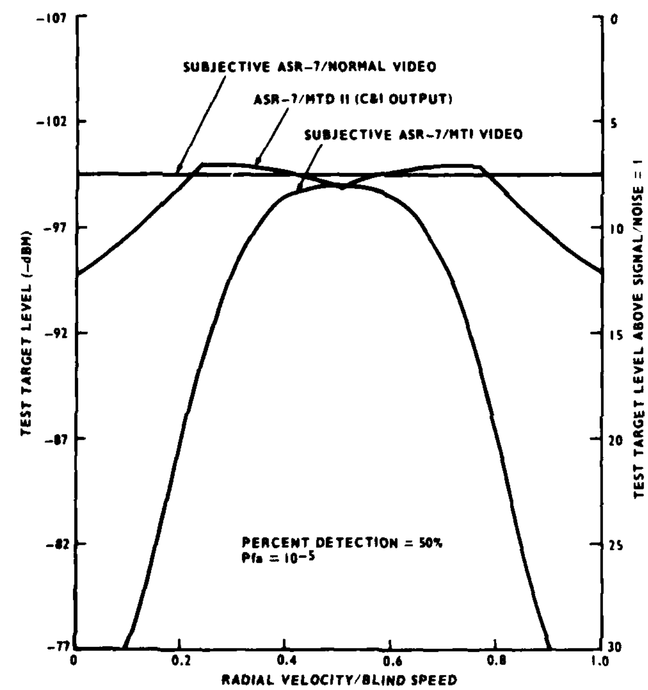

FIGURE 14. PERCENT OF DETECTION (ASR-7/MTD II AND ASR-7/MTI NORMAL VIDEO)

for sweep intensity level display range, false alarms are nonexistent, etc. The visibility threshold for the ASR-7 is 2.2 dB above unity (reference 4). This signal level is unsuitable for air traffic control. The detectability threshold, however, which is suitable for air traffic control, takes into account the factors of visual search. Data presented by Williams (reference 4), who used a target having dimensions very similar to the ASR-7, shows that an increase of 12 dB (above the visibility factor) was required to detect a target about 4 inches from where the operator's eyes were fixed. Data reported by Harriman (reference 4) compared search time in seconds to signal level above visibility threshold. These data are shown in figure 15. For the ASR-7 scan time of 4.7 seconds, a target level of 11 dB above the visibility threshold would be required for detection.

Harriman (reference 4) used a target having dimensions of 1/2 microsecond x 1° for which the observer had to search on a 7-inch diameter radar display. As plotted, it appears that targets at the visibility threshold and 2 dB (4.2 dB above unity) above it were equally difficult to detect. Additional data, which were collected by Offi (references 5 and 6), compared the ATC general method of rating radar performance to data collected using a radar data measuring system (RDMS). (An operator rated the return according to an estimated intensity gradient factor ranging from 0 (no target) to 4 (maximum). This level is subjectively determined by the individual controller.)

The RDMS measured signal strength above unity. Data were recorded from approximately 300 antenna scans using targets of opportunity with the following results:

Controller Grades	RDMS Reading in dB Above Unity
0	0 to 6
1	3 to 15
2	12 to 24
3	19 to 28
4	24 to 32

In a separate project (reference 5), it was determined with the RDMS that a minimum usable target threshold level corresponded signal-to-noise ratio of 8 dB. Figure 14 shows the subjective 50-percent dectection of the ASR-7 plotted against radial velocity.

VELOCITY RESPONSE. The velocity response of the ASR-7/MTI is a site-dependent parameter which is adjusted for the optimum tradeoff between MTI clutter residue and aircraft detection at low radial velocities. The ASR-7/MTI in Burlington, Vermont, was operated in the dual canceller mode. Figure 16 shows the measured unambiguous velocity response of the ASR-7/MTI in the dual canceller mode. The MTI velocity response in Burlington, Vermont, was limited to 27 dB by the receiver limiter. The receiver limiter is adjusted for the optimum tradeoff between the MTI improvement factor and the amount of MTI clutter residue (false alarms) seen by the air traffic controller.

The velocity response of the MTD II was measured by applying a near limit level signal at video from a variable phase function generator and recording the magnitude (see appendix A) output in 25-Hertz (Hz) steps. Figure 17 depicts the unambiguous velocity response of the MTD II FIR filters. Since Doppler filters 5, 6, and 7 are mirror images of filters 3, 2, and 1 they are not included, but can be deduced from the data shown.

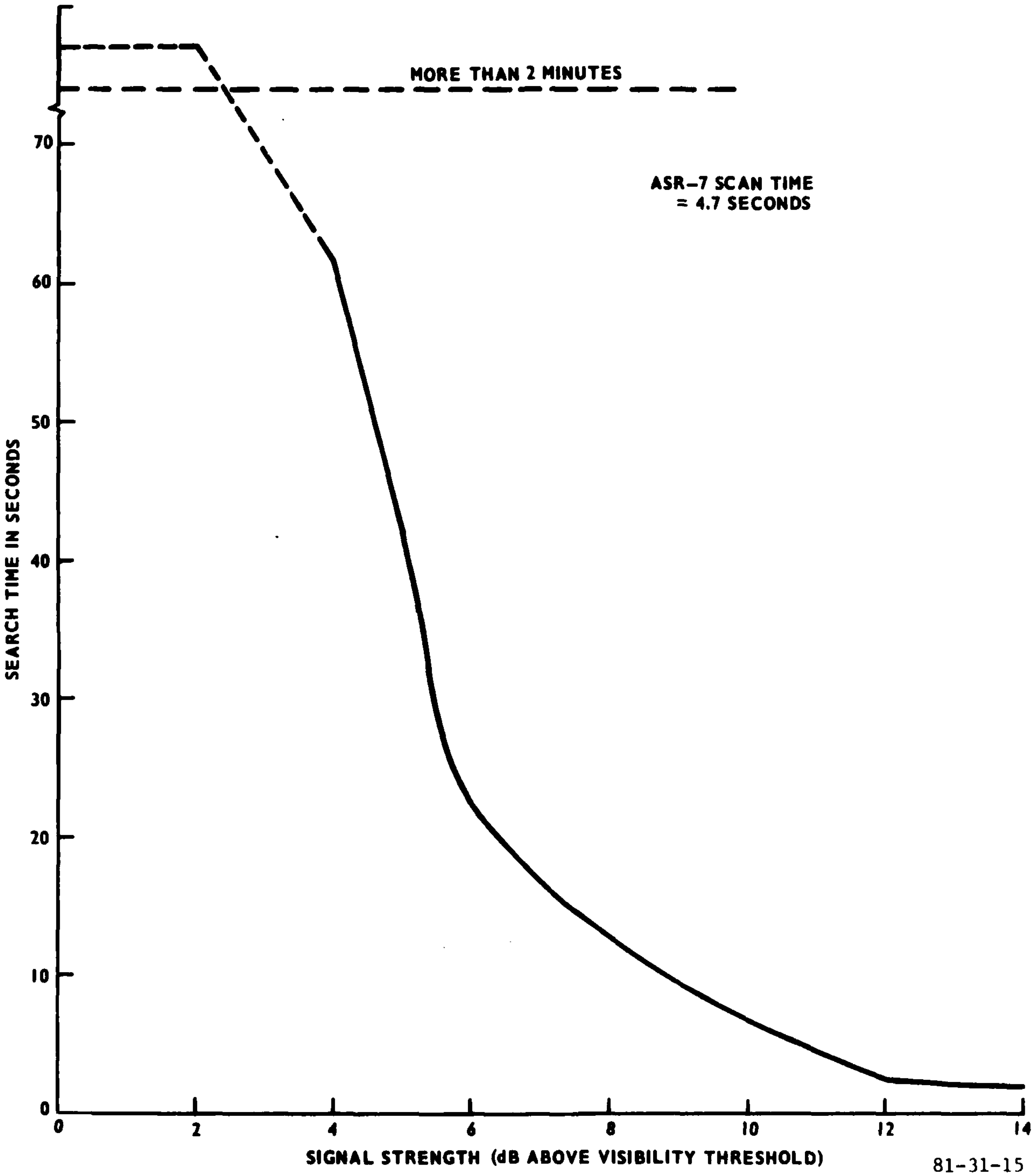

FIGURE 15. SEARCH TIME VERSUS SIGNAL STRENGTH

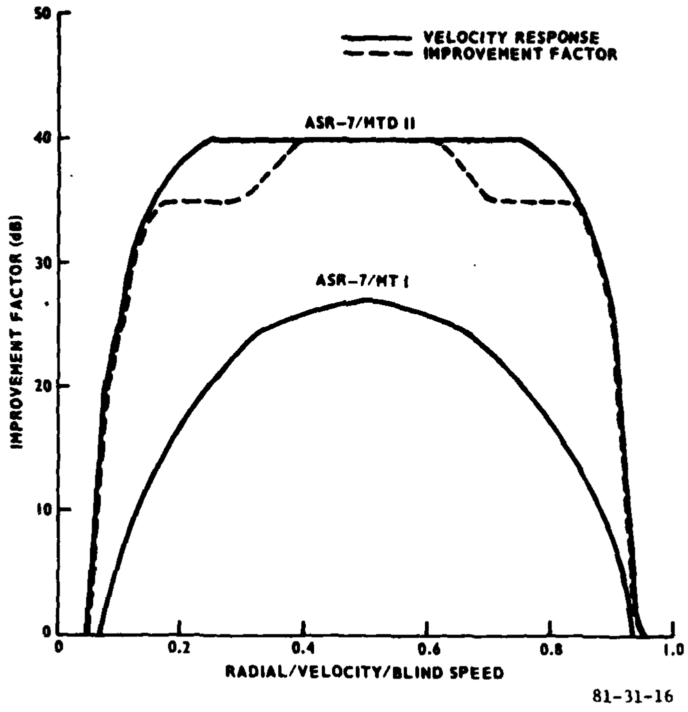

FIGURE 16. IMPROVEMENT FACTOR AND VELOCITY RESPONSE OF ASR-7/MTI AND ASR-7/MTD II

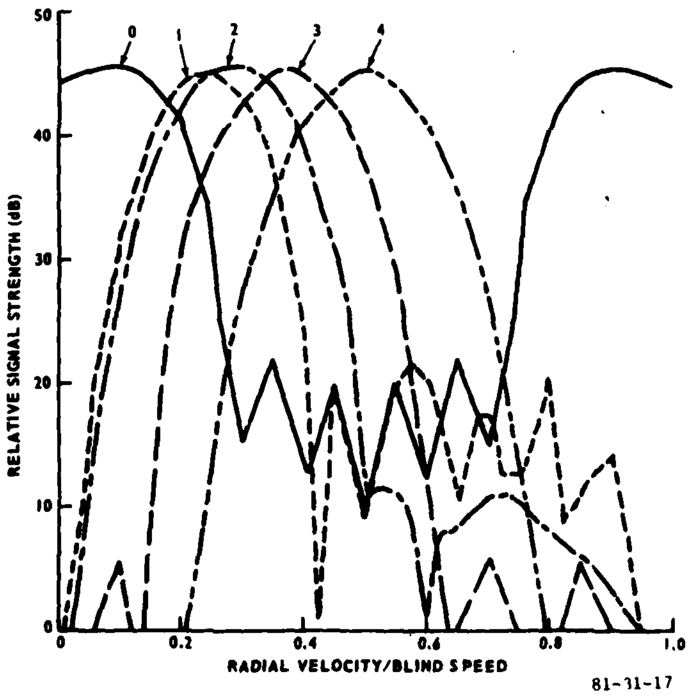

FIGURE 17. VELOCITY RESPONSE OF MTD II FILTERS

Figure 16 compares the composite unambiguous velocity response of the seven non-zero Doppler filters of the MTD II with the ASR-7/MTI. The MTD II velocity response was effectively limited to 40 dB by the ASR-7 instability (discussed in the section on MTD II improvement factor). The MTD II velocity response provided a significant improvement in aircraft detection at low radial velocities over the ASR-7/MTI dual canceller mode while still providing sufficient filtering for maintaining the false alarm rate at 40 per scan (1×10^{-5} Pfa).

The MTD II Doppler filter side-lobe levels have been significantly lowered over the MTD I. Table 1 is a comparison of side-lobe levels of the MTD II and MTD I. The side-lobe levels in table 1 are derived from the peak of the main lobe to the peak of the highest side-lobe. The velocity response and side-lobe levels of the MTD I are shown in figure 18.

The MTD II Doppler filter widths have been broadened significantly. Table 2 is a comparision of the Doppler filter widths (10 dB down from their peaks) in radial velocity.

TABLE 1. COMPARISON OF MTD II AND MTD I DOPPLER FILTER SIDE-LOBE LEVELS

	MTD II (dB)	MTD I (dB)
Filters 1 and 7	23.5	12
Filters 2 and 6	35	18
Filters 3 and 5	39	26
Filter 4	46.5	46.5
Filter 0	22	11

TABLE 2. COMPARISON OF MTD II AND MTD I DOPPLER FILTER WIDTHS

	MTD II (knots)	MTD I (knots)
Filter 1 and 7	27.69	19.7
Filter 2 and 6	29.28	23.9
Filter 3 and 5	30.88	24.49
Filter 4	31.95	25.56
Filter 0	25.56	18.41

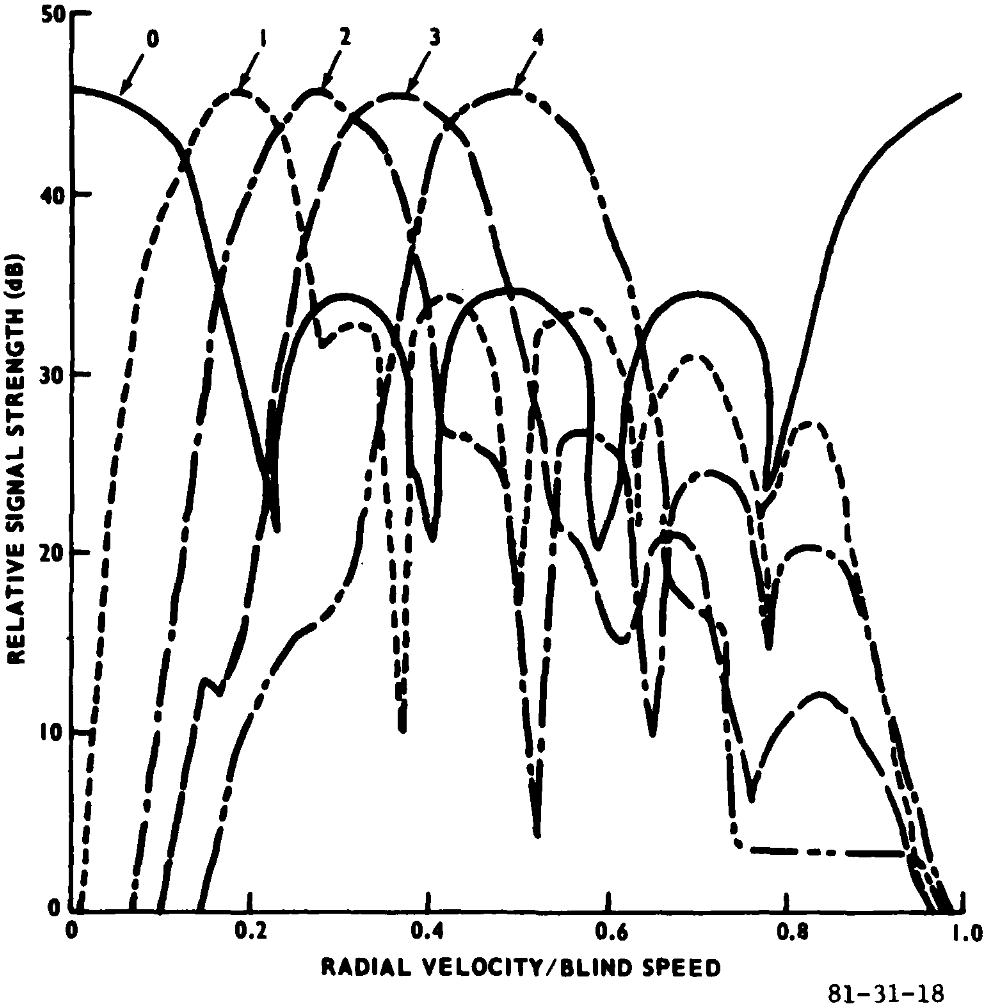

FIGURE 18. VELOCITY RESONSE OF MTD I FILTERS

The center of the lower radial velocity MTD II Doppler filters has been shifted significantly with respect to the MTD I.

Table 3 compares the radial velocity at the center of each Doppler filter assuming a pulse repetition frequency (PRF) of 1000 Hz.

The MTD differs from other radar processors (ARTS IIIA Radar Data Acquisition System (RDAS)) and conventional analog processors (MTI) by its ability to threshold on chosen small radial velocity segments independently of others. This simple but important approach to radar processing (better adhered to in the MTD I) provides a very low system false alarm rate with excellent aircraft detection, as demonstrated by the MTD I in tests at the FAA Technical Center. The MTD II Doppler filter implementation has resulted in a decrease in velocity discrimination. This poorer performance was caused by shifting the radial velocity of Doppler filters 1 and 7 and increasing Doppler filter widths of the MTD II by approximately 7 knots (as discussed previously) resulting in a reduction of aircraft detection at low radial velocities and poorer false alarm control.

The reduction of aircraft detection at low radial velocities and poorer false alarm control have taken place because the velocity filter implementation has reduced the difference in radial velocity between Doppler filters 1 and 2 or 6 and 7 at the filter 3 dB point from the peak of the filter, to only 3.19 knots in the MTD II, as compared to 9.58 knots in the MTD I. The MTD I took advantage of this radial velocity discrimination capability in processing angel clutter and antenna modulated

TABLE 3. COMPARISON OF MTD II AND MTD I DOPPLER FILTERS CENTER RADIAL VELOCITY

	MTD II (knots)	MTD I (knots)
Filter 1	26.62	19.17
Filter 2	30.88	28.75
Filter 3	40.73	40.40
Filter 4	53.25	53.25
Filter 5	66.03	66.10
Filter 6	75.61	77.75
Filter 7	79.80	87.33

ground clutter by having a separate threshold in each Doppler filter for angel clutter and separate threshold in Doppler filters 1 and 7 for ground clutter. The MTD II selective thresholding consists of applying the same threshold in Doppler filters 1, 7, 2, and 6 for antenna modulated ground clutter. For angel clutter removal in the MTD II, the Doppler filters are combined into four filter groups (0; 1 and 2; 6 and 7; 3, 4 and 5) with a separate threshold applied to each group. In addition, the MTD II filter implementation required the zero-Doppler filter width to be increased which has reduced the coherent gain of the MTD II zero-filter with an accompanying decrease in sensitivity. This shift has also caused the first staggered PRF blind speed null to be 16 dB with the MTD II compared to 7 dB with the MTD I (blind speeds are covered in the next section).

The area where the MTD II Doppler filters may offer improvement is in the detection of aircraft in precipitation clutter. This possible improvement is based upon the fact that the side-lobe levels of the MTD II are lower. However, the Doppler filter widths are approximately 7 knots wider, and the 3.19-knot difference in radial velocity between Doppler filters 1 and 2 or 6 and 7 in the MTD II, which may negate this improvement. System testing in precipitation clutter was not accomplished at Burlington, Vermont.

The measured overall velocity responses of the ASR-7/MTI, MTD II, and MTD I are shown in figure 19.

The MTD velocity response shown does not include the zero-Doppler filter. The dips in velocity response are caused by blind speed nulls. Aircraft detection may also occur on the ASR-7/normal video or zero-Doppler filter of the MTD. As seen in figure 19, the width and depth of the blind speed nulls of the ASR-7/MTI (dual canceller mode) are larger than those generated by the MTD II Doppler filters. The width of the first blind speed null 8 dB down from the peak in the ASR-7/MTI response is 45 knots compared to 20 knots for the MTD II.

The blind speed nulls of the MTD II compared to the MTD I are deeper and wider. This degradation is the result of moving the center of Doppler filters 1 and 7 from 0.18 to 0.25 (Doppler frequency/PRF). The depth of the first blind speed null of MTD II is 16 dB compared to 7 dB for the MTD I.

Therefore, while the MTD II provides an improvement in clutter reduction and target detection over the ASR-7/MTI, it does not provide as good a capability as was obtained from the MTD I.

<u>ASR-7/MTI AND ASR-7/MTD II IMPROVEMENT FACTOR</u>. The figure of merit for an MTI system is the improvement factor which is defined as output ratio of target-to-clutter divided by the target-to-clutter ratio at the input (reference 2).

The limitations on the *attainable* MTI or MTD improvement factor are radar instabilities (transmitter, stalo, coho, coho locking pulse timing, etc.), the dynamic range of the receiver/processor chain (limiting), quantization noise of the analog-to-digital converters, and scanning motion of the antenna.

The stability of the ASR-7/MTD II was measured in two ways using the Single Gate Processor (SGP) Fast Fourier Transform (FFT) analysis routine provided with the system. In the first method, the radar antenna was spotlighted (nonscanning) on a fixed piece of nonlimiting ground clutter; and in the second method, the echo box signal was used to substitute for the ground clutter.

Figures 20 and 21 are photographs of the SGP routine output with the clutter and echo box methods, respectively. The

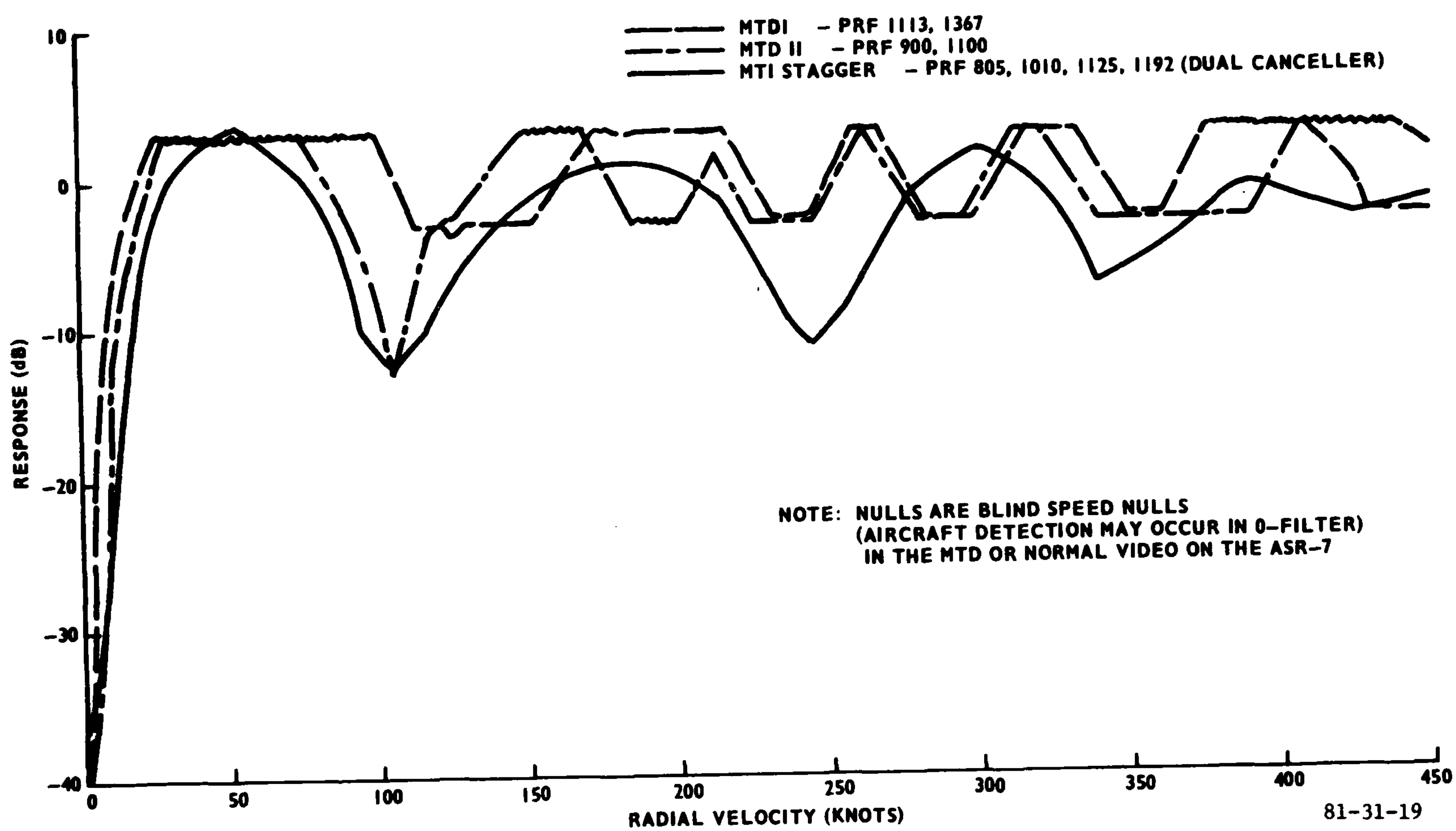

FIGURE 19. OVERALL VELOCITY RESPONSE OF ASR-7/MTI, MTD I, AND MTD II

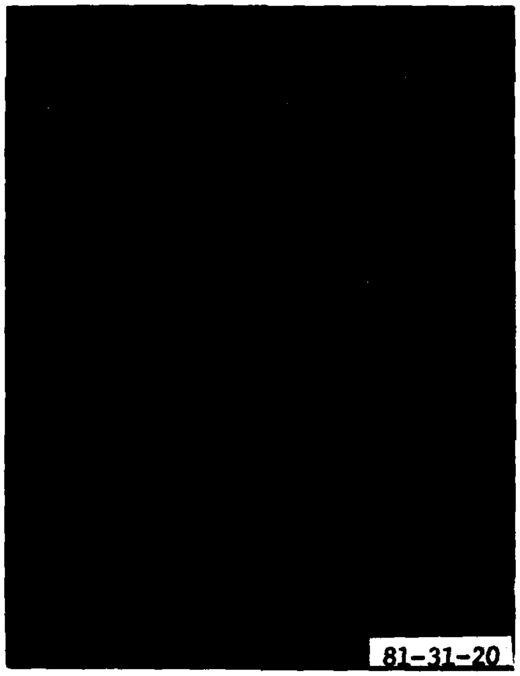

FIGURE 20. ASR-7/MTD II SYSTEM STABILITY (GROUND CLUTTER AMPLITUDE, 40 dB)

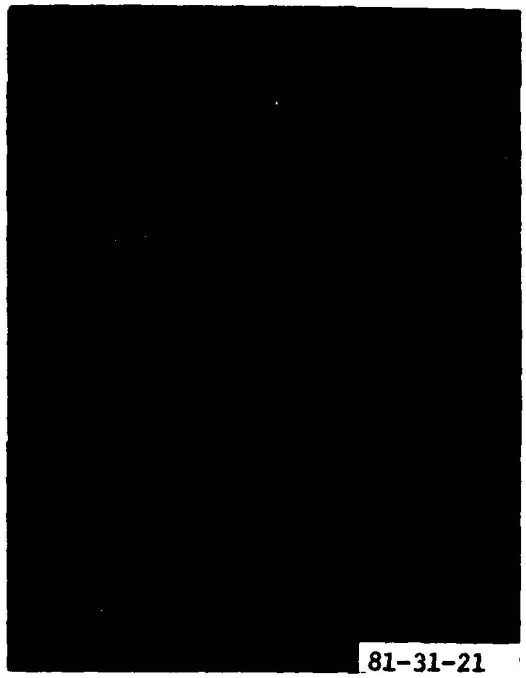

FIGURE 21. ASR-7/MTD II SYSTEM STABILITY (ECHO BOX AMPLITUDE, 40 dB)

center of the horizontal scale in each photograph represents 0 frequency. Negative Dopplers are to the left of 0, and positive Dopplers are to the right. The 64 segments of the horizontal axis mark the 64 outputs of the FFT which covered the unambiguous Doppler range of the radar. The zero-Doppler is at the center, and maximum Doppler is at both edges of the display. The figure of merit in this test is the difference in amplitude between the desired fixed-clutter zero-Doppler response and any spurious frequencies generated by system noise, instability, etc.

After 18 dB for the coherent gain of SGP routine are subtracted, figures 20 and 21 represent the stability of ASR-7/MTD II. Both figures indicate the stability of the system to be about 40 dB above RMS noise. The difference in noise level between figures 20 and 21 is due to the different gain index used in the SGP routine.

Both figures 20 and 21 represent responses from clutter whose amplitude was approximately equal to the stability of the ASR-7/MTD II. Figure 22 represents a response from clutter (echo box generated, 43 dB in amplitude) which exceeds the stability figure of merit of 40 dB above RMS noise. Note the increase of spurious frequencies across the entire unambiguous Doppler range.

This increase of spurious frequencies by clutter whose amplitude exceeds the stability of the ASR-7/MTD II results in false alarms. To prevent false alarms from being generated by clutter which exceeded 40 dB at Burlington, Vermont, a portion of the clutter map (zero filter) threshold level was added to the mean level threshold of all Doppler filters.

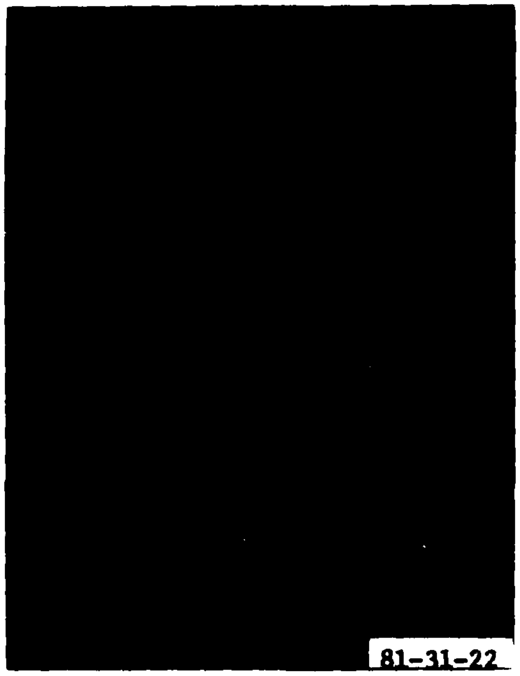

FIGURE 22. ASR-7/MTD II SYSTEM STABILITY (ECHO BOX AMPLITUDE, 43 dB)

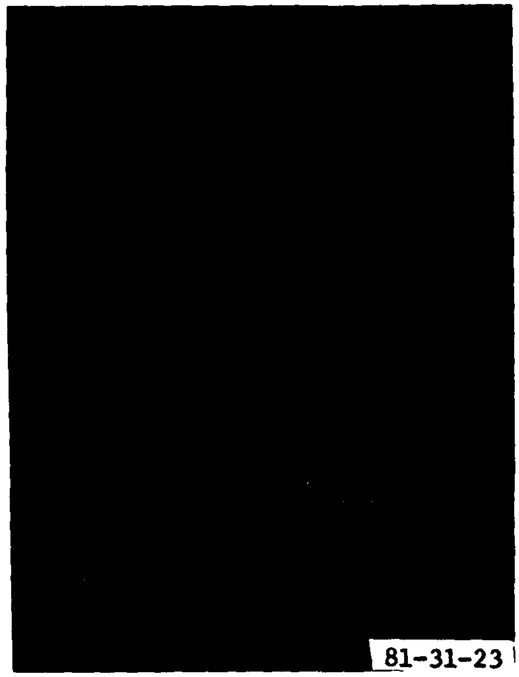

FIGURE 23. ASR-8/MTD II SYSTEM STABILITY (GROUND CLUTTER AMPLITUDE, 50 dB)

The mean level threshold was increased only on clutter which exceeded 40 dB.

The instability which occurred with clutter above 40 dB was apparently caused by problems in the ASR-7 (magnetron or coho phase locking circuit.) Figure 23 is an SGP photograph showing the improvement obtainable with the MTD II operating with an ASR-8 (a Klystron system). The improvement factor of the ASR-8/MTD II is greater than 50 dB.

The improvement factor of the ASR-7/MTD II in Doppler filters 3, 4, and 5 was limited to 40 dB by the radar system instability. The improvement factor in Doppler filters 1, 2, 6, and 7 was limited to 35 dB by antenna modulated ground clutter and Doppler filter design. To maintain the ground clutter false alarm rate to 1×10^{-5} in these filters it was necessary for any ground clutter cells which exceeded 35 dB above rms noise to add a portion of the zero filter threshold that was directly proportional to the amplitude of the clutter above 35 dB to the mean level threshold.

The improvement factor of the ASR-7/MTI (operating in dual canceller mode) was limited to 27 dB by the receiver limiter used to reduce clutter residue. The improvement factor of the ASR-7/MTI and ASR-7/MTD II is shown in figure 16.

SUBCLUTTER VISIBILITY. The subclutter visibility (SCV) of a radar system is a measure of its ability to detect moving target signals superimposed on clutter signals (reference 2). The SCV of a radar is less than the improvement factor by the visibility factor. The visibility factor for the ASR-7/MTD II, as discussed in the section on Pd, is 7.5 dB above unity signal-to-noise ratio for a 50-percent detection and 1×10^{-5} false alarm rate. The limited SCV at the center frequency of Doppler filters 3, 4, and 5 is 40 dB - 7.5 dB = 32.5 dB; in Doppler filters 1, 2, 6, and 7 is 35 dB - 7.5 dB = 27.5 dB.

The subjective visibility factor for the ASR-7/MTI, as discussed in the section on Pd, is about 8 dB above unity signal-to-noise ratio.

To verify the visibility factor, SCV measurements were made on both systems using a simulated antenna modulated TTG signal superimposed over ground clutter returns and also over returns generated by the echo box. Since ground clutter returns vary considerably from scan to scan, the echo box provided the most accurate results. Results from both methods, however, showed agreement. Figure 24 shows the SCV obtained for the MTD II and the ASR-7/MTI. Each system was measured with several levels of clutter, but the clutter level which provided the highest SCV was equal to the maximum improvement factor of each system.

<u>FLIGHT TESTS</u>. Results from three areas of comparative performance flight testing are presented below. These areas are system sensitivity, tangential target detection in the clear and in clutter, and subclutter visibility. Data were collected simultaneously from the standard ASR-7 channel (channel B)

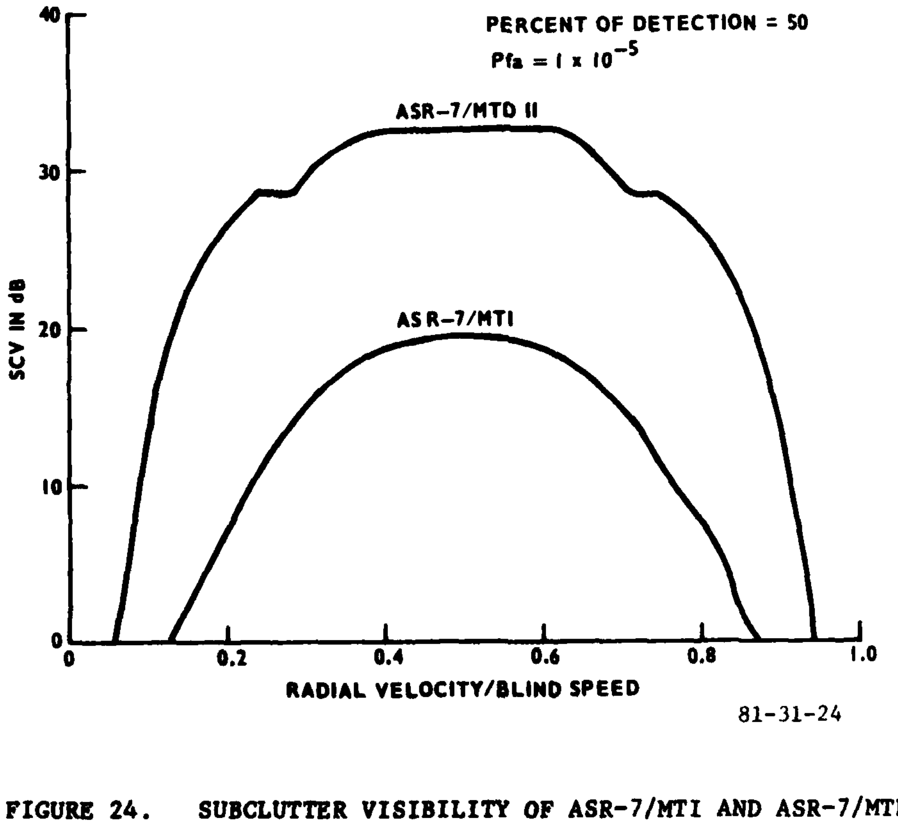

FIGURE 24. SUBCLUTTER VISIBILITY OF ASR-7/MTI AND ASR-7/MTD II

used for ATC purposes and from the ASR-7 channel (channel A) used by the MTD II.

A video recorder recorded normal and MTI video from the ATC channel while a digital recorder recorded the MTD II output. Both channels used their own STC curves. The following data are derived from only one flight test, but represent the performance achieved by the MTD II daily in Burlington, Vermont.

Sensitivity. Sensitivity flight testing was conducted to determine the comparative performance of two radar/processor systems (ASR-7/MTD II and the ASR-7/MTI video) in the detection of a low-flying small aircraft. This was done at the outer limit of radar coverage in a clutter free environment. To accomplish this, a Cessna 152 test aircraft flew at 1,000 feet until detection was lost and then was turned around until detection was reestablished. This loss of detection occurred at approximately 20 nmi for both radar/processor systems. This zone of marginal detection was tested four times with the edge given to the MTD II by the air traffic controller controlling the test aircraft.

Tangential Target Detection In The Clear. Tangential target detection tests were conducted in a clutter free environment on the same day as the sensitivity tests using the Cessna 152.

The Cessna 152 was flown on a course which kept the radial velocity at 0 or slightly above at a range of 25 nmi (in the MTI region) and an altitude of 4,000 feet. The test lasted for 57 scans with the following detection results:

ASR-7/MTI = 21 percent
ASR7-/MTD II = 94.7 percent

Tangential Target Detection In Clutter. Tangential target detection over clutter was conducted by flying the test aircraft over clutter which averaged 20 dB above noise at a range of 27 nmi and an altitude of 4,000 feet. The test aircraft was flown on a course which kept the radial velocity at 0 or slightly above. The test duration was 38 scans with the following detection results:

ASR-7/MTI = 0 percent
ASR-7/MTD II = 67.56 percent

Overall Results of Tangential And Sensitivity Flight Test. The Cessna 152 departed Burlington Airport on January 9 and was detected at 0.5 nmi by both the ASR-7/MTD II and ASR-7/MTI. The aircraft proceeded outbound where a loss of detection occurred in four scans inside 6 nmi on the ASR-7/MTI system. The ASR-7/ MTD II surveillance processor output coasted (no detection present) for eight scans during the same period. However, the test aircraft was detected six out of the eight scans by the MTD II, but the target information was lost during processing.

There is a strong possibility that the target information was lost in the RAG cells on at least four scans. The aircraft proceeded outbound where the sensitivity and tangential tests took place.

Upon completion of the tests, the test aircraft proceeded to Burlington Airport from a range of 25 nmi. The ASR-7/MTI did not detect the test aircraft on 11 scans in addition to those already mentioned. The ASR-7/MTD II during the same period recorded no loss in detection. At 6 nmi from the airport, the test aircraft was forced to enter a holding pattern where the ASR-7/MTI system did not detect aircraft on 38 scans out of 133. In fact, for several minutes the exact location of the aircraft was unknown by the air traffic controller using the ASR/MTI system. During the same period ASR-7/MTD II detection was virtually 100 percent (one scan was lost).

The overall detection results for the entire flight test were:

ASR-7/MTI = 79.2 percent
ASR-7/MTD II = 95.0 percent

Subclutter Visibility. The SCV of the two systems (ASR-7/MTD II and ASR-7/MTI video) was compared by flying the Cessna 152 over clutter of two different levels. The first level of clutter exceeded the MTD II improvement factor and averaged 50 dB or greater. The second level of clutter averaged just under 40 dB, which is the maximum improvement factor obtained by the MTD II on a magnetron radar. Any data obtained while the test aircraft was flying tangentially were not used in the subclutter visibility test.

The test duration over 50 dB clutter was 135 scans after the tangential data were removed with the following detection results:

ASR-7/MTI = 10 percent
ASR-7/MTD II = 70 percent

The test results after flying test aircraft 242 scans over 40 dB clutter were:

ASR-7/MTI = 28.9 percent
ASR-7/MTD II = 83.4 percent

The maximum SCV capabilities of the respective systems can be ascertained from figure 24.

SUMMARY OF RESULTS

1. The MTD II system probability of false alarm in thermal noise was set to 1×10^{-5} by a mean level threshold of 13.8 dB above rms noise in Doppler filters 1 through 7.

2. The MTD II system false alarm rate in ground clutter and moving ground traffic was 1×10^{-5}. This was achieved by removing the RAG attenuation and censoring, reducing the range extent of R^{-4} STC curve from 13.75 nmi to 7.7 nmi, and by the use of a simulated dual receive beam (passive horn) antenna.

3. The ground clutter and moving ground traffic false alarm rate (clutter residue) of the ASR-7/MTI is higher than 1×10^{-5}, which degrades target detection.

4. The MTD II processor has a linear dynamic range capability of 51 dB above rms noise, an increase of 8 dB over the MTD I. The MTD II system linear dynamic range, however, was limited to 47 dB by the receiver's analog limiter.

5. The ASR-7/MTI system as configured by the Burlington, Vermont, clutter environment had a linear dynamic range of 27 dB.

6. The MTD II system had a 50-percent detection at a test target signal level of 7.5 dB above unity signal-to-noise ratio with a probability of false alarm of 1×10^{-5}.

7. The ASR-7/MTI had a subjective 50-percent detection (visibility factor) at a test target level of 8 dB above unity signal-to-noise ratio with a probability of false alarm of 1×10^{-5}.

8. The velocity response of the MTD II FIR filters is a significant improvement over that of the ASR-7/MTI (dual canceller mode used in operation at Burlington, Vermont).

9. In staggered PRF operation, the width and depth of the blind speed nulls in the velocity response are less for the MTD II than for the ASR-7/MTI.

10. The blind speed nulls in the velocity response of the MTD II as compared to the MTD I are deeper and wider. The depth of the first blind

speed null of the MTD II is 16 dB down compared to 7 dB for the MTD I.

11. The MTD II Doppler filter design has caused a degradation in SCV and aircraft detection in angel clutter.

12. The system stability of the ASR-7/MTD II was 40 dB at Burlington, Vermont.

13. The improvement factor of the ASR-7/MTD II was 40 dB while that of the ASR-7/MTI was 27 dB.

14. The SCV of the ASR-7/MTD II was 33 dB for an optimum velocity target while that of the ASR-7/MTI was 19 dB.

15. Flight tests showed that the ASR-7/MTD II and ASR/MTI had equal system sensitivity.

16. The percent of detection for tangential flight testing in the clear was 95 percent for the ASR-7/MTD II and 21 percent for the ASR-7/MTI.

17. The percent of detection for tangential flight testing over clutter was 68 percent for the ASR-7/MTD II and 0 percent for the ASR-7/MTI.

18. The percent of detection for the combined sensitivity and tangential flight testing was 95 percent for the ASR-7/MTD II and 79 percent for the ASR-7/MTI.

19. The percent of detection for flight tests over clutter which averaged 50 dB in amplitude was 70 percent for the ASR-7/MTD II and 10 percent for the ASR-7/MTI.

20. The percent of detection for flight tests over clutter which averaged 40 dB in amplitude was 83 percent for the ASR-7/MTD II and 29 percent for the ASR-7/MTI.

CONCLUSIONS

From the results, it was concluded that:

1. The Airport Surveillance Radar (ASR-7) Moving Target Detector (MTD) II system is significantly superior to the ASR-7 Moving Target Indicator (MTI) system in false alarm control and aircraft detection.

2. Use of a dual receive beam (passive horn) antenna to reduce the number of system false alarms caused by heavy ground clutter is preferable to the use of a heavy sensitivity time control (STC) curve or excessive range azimuth gating cell attenuation and censoring which degrade target detection capability.

3. The MTD II Doppler filter design results in degraded aircraft detection.

RECOMMENDATIONS

It is recommended that:

1. The Moving Target Detector (MTD) processor concept be used in all future Federal Aviation Administration (FAA) airport surveillance radar systems.

2. A cost-benefit analysis be performed to determine the desirability of retro-fitting existing FAA airport surveillance radar systems and automated systems (Automated Radar Terminal System (ARTS) IIIA Radar Data Acquisition System (RDAS)) for MTD operation.

3. Future MTD processors should be programmable so the Doppler filter characteristics can be optimized. The Doppler filters should have narrow passbands, a center radial velocity which allows a maximum velocity discrimination between filters while maintaining low side-lobes in order to

enhance target detection in a clutter environment, and provide a 40 decibel (dB) Moving Target Indicator (MTI) improvement factor for Doppler filters 1 and 7.

4. A passive horn antenna should be used to reduce false alarms from high amplitude ground clutter and vehicular traffic instead of the heavy sensitivity time control (STC) and extensive range azimuth gating (RAG) censoring and attenuation used at Burlington, Vermont. For those areas where vehicular traffic false alarms persist, RAG attenuation and/or censoring should be implemented but the RAG cell size should not exceed 1.4° or 0.125 nautical miles (nmi).

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APPENDIX A

MOVING TARGET DETECTOR (MTD) SYSTEM DESCRIPTION

The moving target detector (MTD) II was designed to improve radar detection of aircraft while simultaneously reducing false alarms from ground clutter, second-time-around ground clutter, precipitation clutter, angel clutter, and interference. To provide the required clutter rejection, the MTD II uses wide dynamic range, coherent signal processing, velocity filtering, and adaptive thresholding.

To accomplish the above, the entire radar coverage area is divided into 512 coherent processing intervals (CPI's) of eight radar sweeps each (at the same radar pulse repetition frequency) having approximately a 0.6° azimuth extent and containing 960 range cells. After Doppler processing, this results in the radar coverage area being divided into 3,932,160 (512 x 960 x 8 Doppler filters) independently thresholded range-azimuth-Doppler cells.

Figure A-1 is a functional block diagram of the MTD II processor. As shown, the Inphase (I) and Quadrature (Q) video outputs from the MTD II analog-to-digital (A/D) converters are entered into the saturation and interference test circuitry, the two-pulse canceller/Doppler processor, and the zero-velocity filter.

The interference test adds the eight I & Q values in azimuth from the same range gate in a CPI according to the formula

$$T = K\sum^{8}(|I(j)| + |Q(j)|)$$

where K is nominally set to 1/2. An interference condition is declared if any one of the eight samples is five times the average computed above. If interference is declared, the output from the range/CPI cell is inhibited.

The saturation test is implemented to prevent processing any I or Q video samples which have limited in the A/D converters. If the saturation test is positive, the range/CPI cell output is also inhibited.

The MTD II filters are implemented by entering eight real and imaginary (I & Q) video samples from each range/CPI cell into a two-pulse canceller producing seven real and imaginary output samples. Following the two-pulse canceller, seven-point finite impulse response (FIR) filters are generated for the non-zero velocity domain. The seven complex samples entered into the filters are multiplied by a set of seven real and complex weights and summed to form the MTD II non-zero velocity filter outputs. The zero velocity filter is generated in the same manner except that eight complex samples are entered to be multiplied by eight real weights and the results are summed. Figures A-2 and A-3 give the calculated values for the MTD II filters. Filters 7, 6, and 5 are mirror images of filters 1, 2, and 3 and are not shown.

The approximate magnitude of each filter is calculated by using the magnitude of (63/64 A+1/4B) or (7/8A+1/2B), whichever is larger, where A is the larger of $|I|$ or $|Q|$ and B is the smaller.

The magnitude of the zero velocity filter, which represents the ground clutter amplitude for each range/CPI cell, is entered into the clutter map. The clutter map is updated each scan by adding one-eighth of the present scan information to seven-eighths of the previous scan values.

The threshold for the zero filter is set 15.56 dB above root mean square (rms) noise level in each range/CPI cell. The threshold for each of the seven non-zero velocity filters is calculated by summing the results of eight range gates before the cell of interest and seven range gates after the cell of interest.

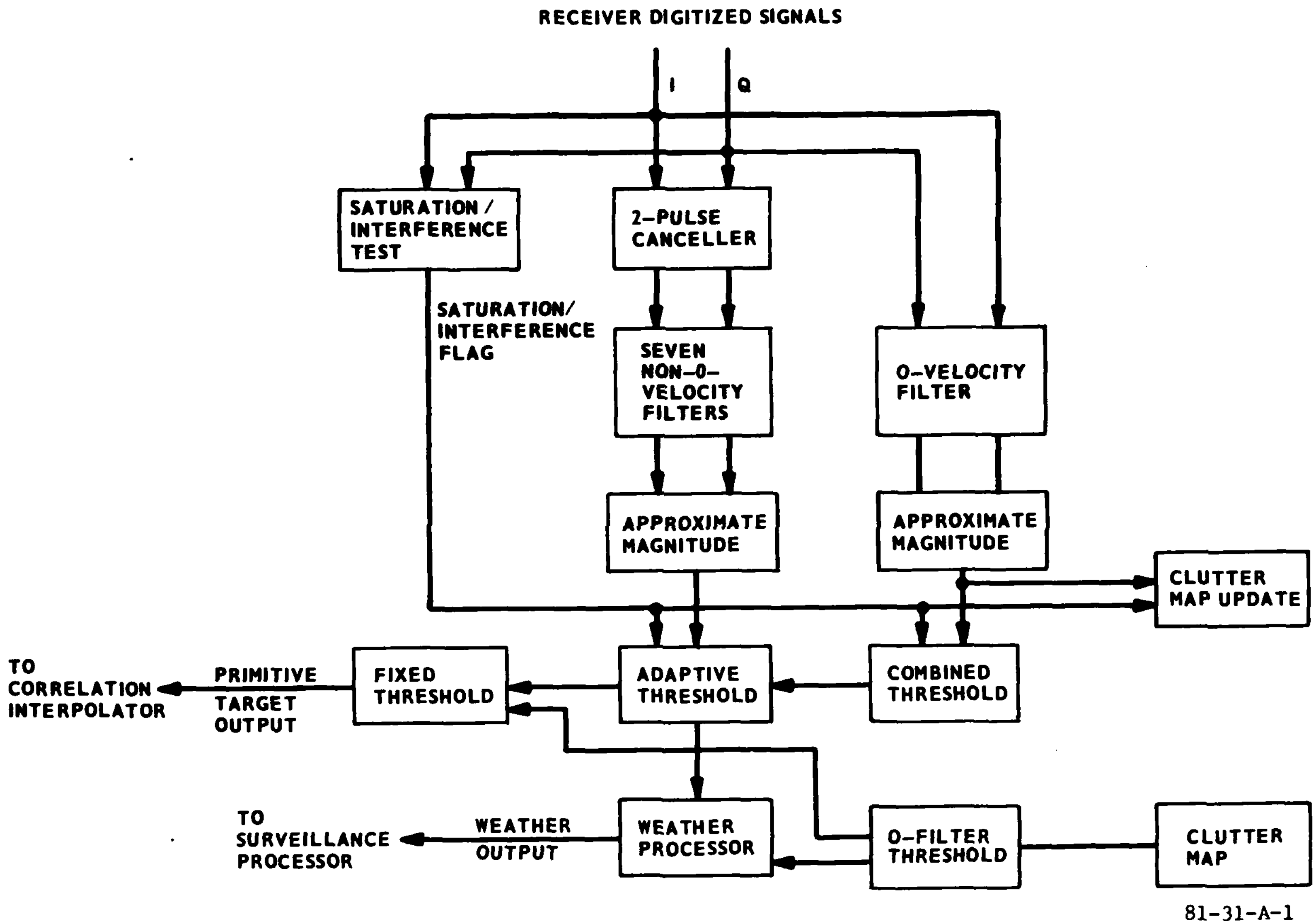

FIGURE A-1. MTD II PROCESSOR BLOCK DIAGRAM

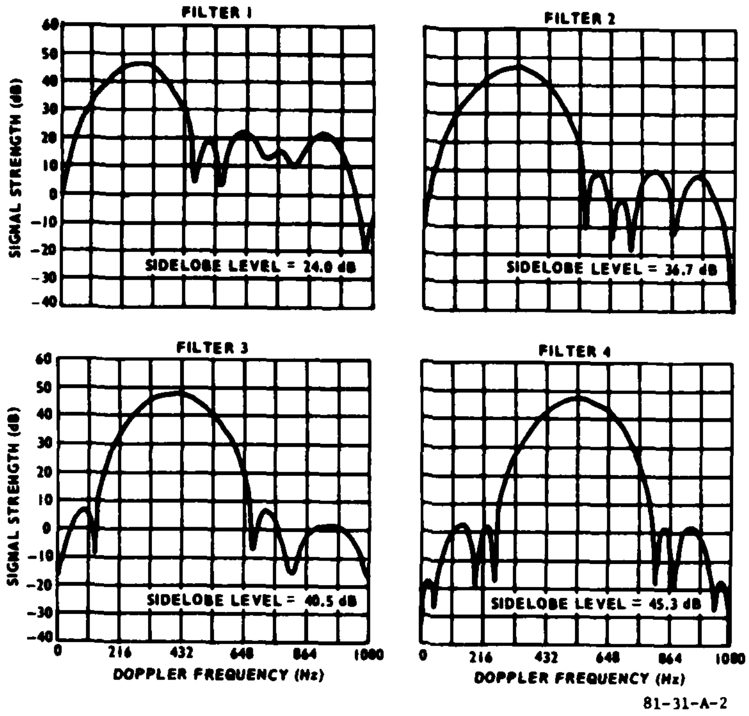

FIGURE A-2. *MTD II COMPUTED DOPPLER FILTER RESPONSE* (FILTERS 1 THROUGH 7)

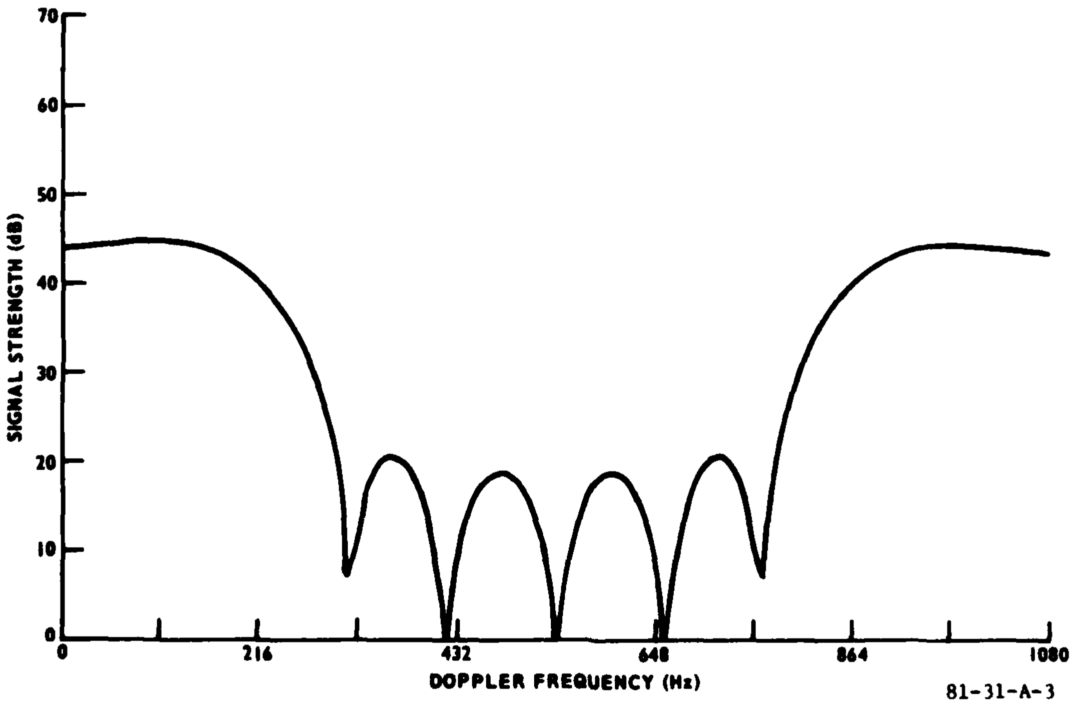

FIGURE A-3. MTD II COMPUTED DOPPLER FILTER RESPONSE (ZERO FILTER)

The value in the range gate before and after the cell of interest is subtracted from the sum. This sum is multiplied by 3/8 to produce the mean level threshold. This corresponds to a threshold 13.8 dB above the rms noise level. In addition to the mean level threshold and zero velocity filter threshold, a combined threshold is calculated where a portion of the zero filter is added to the mean level threshold. There are two uses for this combined MTD II thresholding. The first occurs when the dynamic range of signals at the input (receiver and A/D combination) exceeds the stability of the system (transmitter, stalo, etc.) causing false alarms to be generated on any clutter amplitude that exceeds the stability level of the system. The second is to reduce the false alarms generated by antenna modulation in the low velocity filters. Either of these cases requires thresholding in excess of the mean level threshold to eliminate false alarms generated in conjunction with ground clutter signals. A third fixed threshold is used to remove false alarms caused by A/D quantization noise.

The weather processor module detects two programmable levels of precipitation clutter. The precipitation clutter level for contouring is obtained by summing the seven non-zero velocity filter thresholds over 1-nmi intervals on alternate CPI's. The zero velocity filter output is added to this sum whenever the ground clutter is non-existent or very low compared to the weather level, thus, providing additional low radial velocity weather information. The precipitation clutter levels are rendered accurate at any range by the addition of an R^{-2} curve in the processor at those ranges which are beyond the system STC operation. The precipitation returns within the system STC range are adjusted to compensate for the system STC.

The output of the above MTD II processing is primitive target reports which contain the following information: target range, target azimuth, filter number, target magnitude, and PRF information. This information is entered into the correlation and interpolation (C&I) section of the processor where centroiding, correlating, and thresholding of primitive targets occur as shown in figure A-4. Also, weather information is outputted directly to the surveillance processor.

Immediately following the C&I input buffer, the target primitives are compared to a fixed threshold/censoring map whose function is to remove false alarms generated from limiting ground clutter and ground traffic. The resolution of the threshold/censoring map is 1/4 mile by four CPI's.

Following the fixed threshold/censoring map, the target primitives are compared to a threshold 10 dB less than the threshold generated by the adaptive amplitude censoring which follows C&I. This part of adaptive amplitude censoring is used only under heavy angel activity to make the data load manageable. Otherwise all adaptive amplitude censoring takes place after C&I.

The correlating of primitive targets into a single report is based upon range and azimuth proximity. All primitives adjacent in range and azimuth within three range cells and eight CPI's are correlated to form a single target report. One missed CPI is allowed for blind speed effects.

The interpolation of center position of primitive target clusters is developed first by correcting the primitive target amplitude for different Doppler filter gains. The centroided range and azimuth are calculated by using a center-of-mass technique.

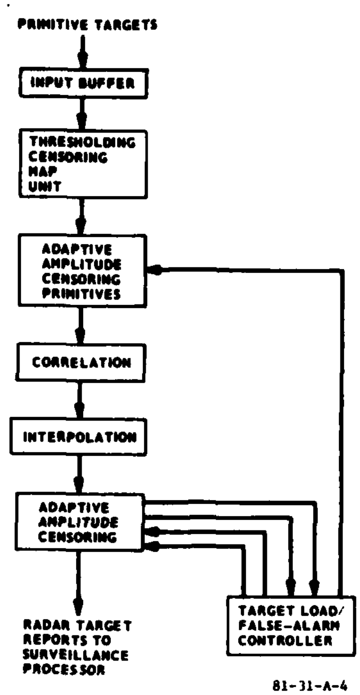

FIGURE A-4. CORRELATION, INTERPOLATION, AND AMPLITUDE CENSORING BLOCK DIAGRAM

The formulas are:

Centroided Range =

$$\frac{\Sigma \text{ amplitude}_i \times \text{range}_i}{\Sigma \text{ amplitude}}$$

Centroided Azimuth =

$$\frac{\Sigma \text{ amplitude}_i \times \text{azimuth}_i}{\Sigma \text{ amplitude}}$$

The function of adaptive amplitude censoring is to control the number of false alarms entering the surveillance processor. The philosophy of false alarm control is to count the ratio of weak targets to strong ones by filter numbers and geographical location over an extended period of time. If the ratio of weak targets to strong targets is high over this time period (50 to 200 scans), attenuation is applied selectively (by Doppler filter number and geographical location) to reduce the number of low amplitude false alarms to approximately 1×10^{-5} (40 false alarms per scan).

The slow-acting thresholding has 880 independent thresholds implemented as follows:

1. Doppler filter groups 0; 1 and 2; 3, 4, and 5; 6 and 7.

2. Ten range bins from 0 to 40 nmi in 4-nmi increments.

3. Four to forty azimuth bins dependent on range: starting at the range interval of 0 to 4 nmi with four azimuth bins per 360°, four additional azimuth bins are added for each 4-nmi range interval up to a maximum of 40.

In addition, a fast-acting threshold is applied to eliminate false alarms occurring at the boundaries. The fast-acting threshold uses the same ratio principle but reacts in two to five scans. The fast-acting threshold is implemented without azimuth discrimination to 20 nmi using two Doppler filter groups (0, 1, 2, 6, 7 and 3, 4, 5).

Following C&I and amplitude censoring, target messages are entered into the Surveillance Processor (SP). Its function is to correlate aircraft reports occurring within three to five scans of each other for display purposes. Figure A-5 is a block diagram of the SP. All the targets from C&I are included on the same display if they are selected by the operator.

The first function of the SP is to associate target reports with existing tracks. This is done by drawing a window about the predicted position of the aircraft. The dimensions of the window about the predicted position are based upon the range and state of the track as shown in table A-1.

Figure A-6 is a state diagram of the SP. The state diagram proceeds as follows: aircraft which are out of track are in state S0. Upon first detection, aircraft enter into S1. A small area is next established about the position of this first detection with dimensions rho (ρ) and theta (θ) equal to the distance a 600-knot velocity aircraft can travel plus an allowance for radar measurement error. If a detection occurs on the next scan in the association area, the arrow marked "P" in figure A-6 is followed to promote the tract to state S2. If no detection occurs, the arrow marked "Q" is followed. As further detection occurs, the track is promoted to higher states until a steady state occurs. The arrows marked P' and Q' represent targets which have not passed minimum distance requirements.

The correlation of target reports with tracks, of course, is trivial where there is only one target to one track (1 on 1) in the association window. For the case of two target reports and one track (2 on 1), the target report with the smallest association measure will be correlated with the track.

The association measure =

$$\sqrt{\frac{\Delta\rho^2}{S\rho^2} + \frac{\Delta\theta^2}{S\theta^2}}$$

where $S\rho$ and $S\theta$ are the radii for the range and azimuth windows for a track in state 2 while $\Delta\rho$ and $\Delta\theta$ are the difference between the predicted position and the actual position of the radar report. For the case of two target reports and two tracks (2 on 2), the target report with the smallest association measure without the loss of correlation to the other track will be correlated.

Following correlation, track updating is required to predict the position of the track on the next scan so that correlation may occur. Inside 8 nmi, for greater accuracy, x and y coordinates are used as follows:

Predicted $x = x' + \dot{x}$
Predicted $y = y' + \dot{y}$

where x' and y' are the measured position this scan, and

$\dot{x} = x' - x''$
$\dot{y} = y' - y''$

where $\dot{x}$ and $\dot{y}$ are the unsmoothed velocity (position change per unit time) where x'' and y'' are the measured position of the past scan.

When the range is beyond 8 nmi, the prediction is done in rho (ρ) and theta (θ) coordinates using α (position) and β (velocity) smoothing for theta (θ) only according to the following rules:

Predicted range $(\rho) = \rho' + \rho$

where ρ' is the measured range this scan, and

$\dot{\rho} = \rho' - \rho''$

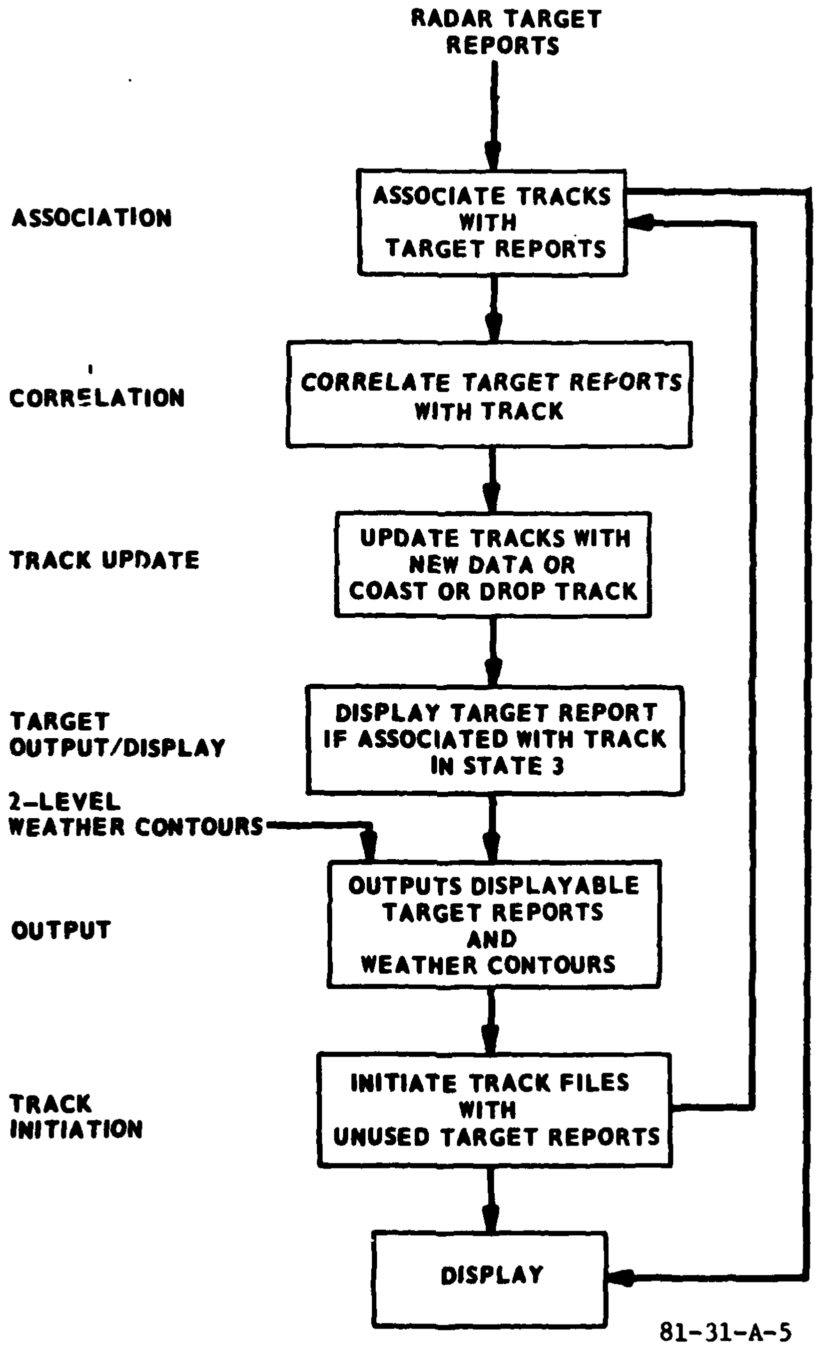

FIGURE A-5. SURVEILLANCE PROCESSOR BLOCK DIAGRAM

TABLE A-1. PREDICTED POSITION OF AIRCRAFT

Track State	Azimuth	Range
S1	±maximum target velocity nominally 600 nmi/hour	±maximum target velocity, nominally 600 nmi/hour
S2, S3, S7	±1.230°, 0.5g acceleration*	±4/32 nmi
S4	±1.230°, 0.5g acceleration*	±7/32 nmi
S5, S6	±1.750°, 1.0g acceleration*	±7/32 nmi

*Acceleration of gravity

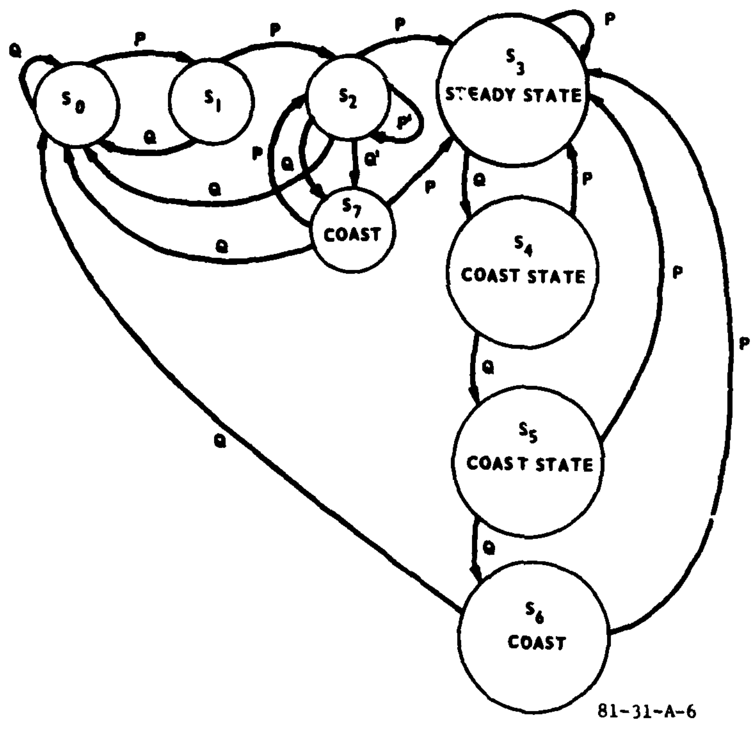

FIGURE A-6. SURVEILLANCE PROCESSOR STATE DIAGRAM where $\dot{\rho}$ is the unsmoothed velocity (positive change per unit time) and ρ'' is the measured range of the past scan.

Predicted azimuth (θ) = $\theta_s + \dot{\theta}_s$ where θs is the smoothed azimuth position, and

$$\theta_s = \theta + \alpha(\theta'_m - \theta_o)$$

where θ_ρ is the smoothed position from the past scan, θ'_m is the measured azimuth on present scan, and θ_o is the predicted azimuth position from the past scan.

$\dot{\theta}_s$ is the smoothed velocity, and $\dot{\theta}_s = \dot{\theta}_v + \beta(\dot{\theta}_m - \theta_o)$ where $\dot{\theta}_v$ is the smoothed velocity from the past scan.

The values of α and β depend upon the quality (strength) of the target signal as follows:

Quality	α	β
3	1.0	0.9
2	1.0	0.9
1	0.9	0.7
0	0.6	0.3

Quality is a measure of the number of CPI's which make up a target with a maximum of two allowed from each PRF.

All target reports which correlate with a track in state 3 will be sent to the display processor.

With some minor exceptions, any target report which does not correlate with a track file is a candidate for a new track.

The display processor permits simultaneous display of MTD target video, MTD weather contour video, beacon video, and map video. The display processor also delays beacon video to allow for the MTD processing delays.

APPENDIX B

SUGGESTED IMPROVEMENTS WHEN OPERATING IN HEAVY GROUND CLUTTER

The following are suggested improvements when operating the Moving Target Detector (MTD) II in heavy ground clutter.

1. The clutter-to-noise ratio should be reduced by the use of a passive horn (gated or ungated) to match as closely as possible the linear dynamic range of the system.

2. The stability of the system (transmitter, coho, stalo, etc.) should be made equal to or greater than the clutter-to-noise ratio if at all possible. A coherent radar (ASR-8) will provide a 10 decibel (dB) increase in stability over that achieved by an incoherent system (ASR-7).

3. If the number of range/azimuth cells in which the clutter exceeds the stability and linear dynamic range of the system is low enough or the cells are geographically scattered, they should not be processed (use the saturation detector to eliminate them entirely).

4. The R^{-4} STC curve should not exceed 12 nautical miles (nmi) in range extent on systems without passive horns.

5. If the above preprocessing optimization has been done and the processing of system limit level ground clutter is still necessary, the following processing should be implemented:

a. Divide all the limiting range/azimuth cells into two categories.

Category 1. Any range/azimuth cell whose clutter level is between limit level and 10 dB above limit level.

Category 2. Any range/azimuth cell whose clutter level exceeds 10 dB above limit level.

b. Assuming all the Doppler filters being used are separate entities (separated in radial velocity), an adaptive thresholding scheme should be setup for each category by Doppler filter. The thresholding should be adaptive to allow the threshold to vary as the clutter-to-noise ratio varies. The cell size should be no larger than 1.5° in azimuth and 0.125 nmi in range. The incrementing and decrementing of the threshold should take place every antenna scan. The incrementing value should be 0.4 dB and decrementing value about 1/25 of the incrementing value. A similar scheme developed at the Federal Aviation Administration (FAA) Technical Center proved effective with the MTD I.

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